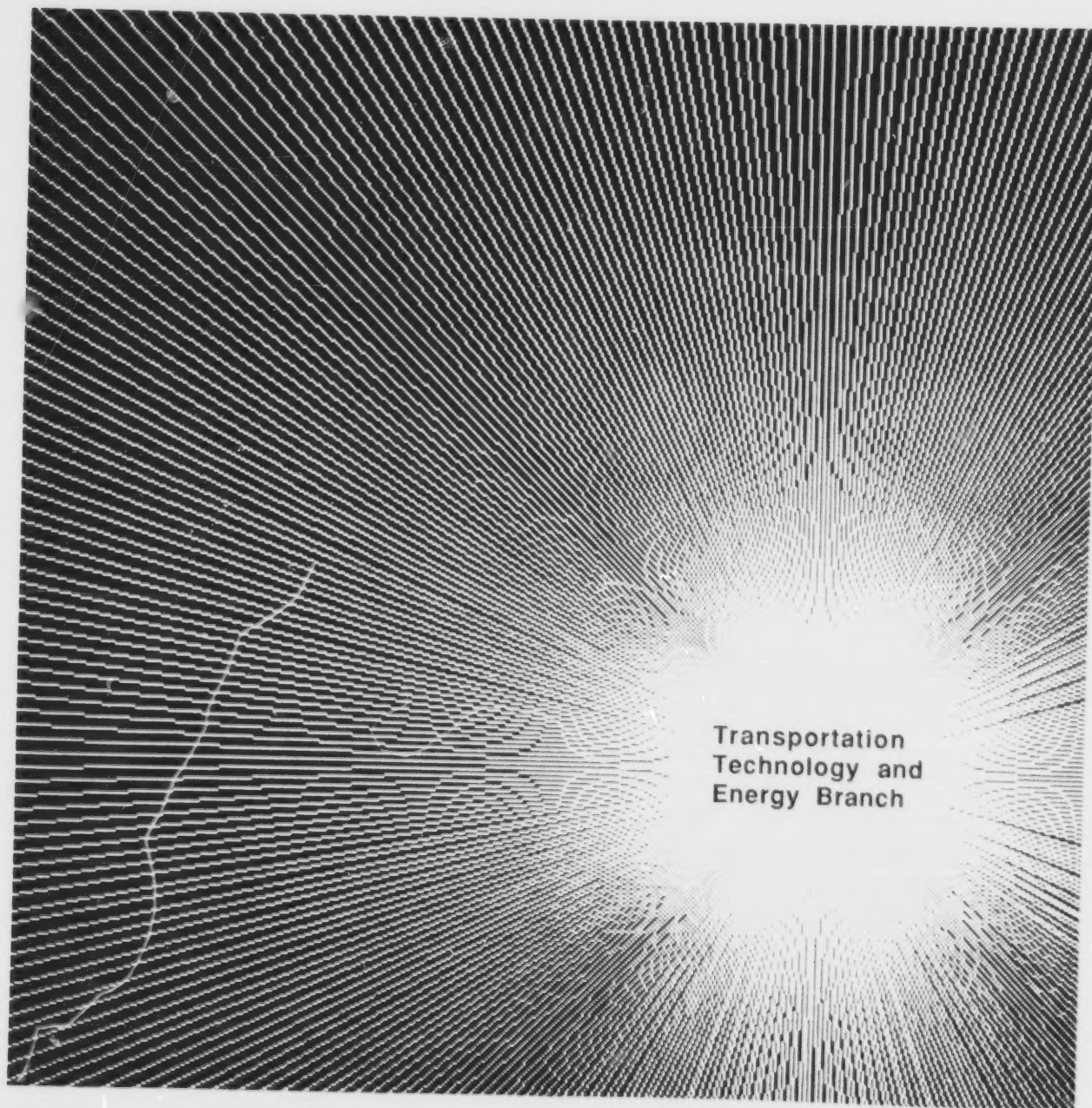




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**Assessment of Transit Bus
Propulsion Options in Ontario**

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Assessment of Transit Bus Propulsion Options in Ontario

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Abstract: This report discusses the 1990-91 status of the technology, economics, and environmental aspects of diesel, propane, natural gas, methanol, and electricity powered transit buses. The relative economics of each of these alternatives is assessed by means of a comprehensive life-cycle cost analysis.

Most of the information used in this analysis and elsewhere in the report is based on the experience generated in research, development, and demonstration projects undertaken by the Ontario Ministry of Transportation.

Disclaimer: This is a research report and does not necessarily reflect ministry policy.

Key words: Transit bus, propulsion, alternative fuels technology, economics, environment, energy, methanol, natural gas for vehicles, propane, electricity.

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Published by:

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EXECUTIVE SUMMARY

Public transit is an indispensable element of transportation in our modern society, and its role is expected to increase. Congestion, with its inevitable side effects of pollution, noise, and excess energy consumption, is a growing concern for large cities.

The diesel bus is the principal vehicle for most transit systems. Its versatility, reliability, and economy are difficult to match by alternative vehicles. However, the future of the diesel bus does not appear to be assured. Concerns about the availability, price, and quality of diesel fuel and, more recently, much greater concerns about the health and environmental effects of diesel engine exhaust emissions have forced suppliers and users to look for alternatives.

In Ontario, the Ministry of Transportation (MTO) has played the lead role in this process of assessing the alternatives to the diesel bus.

In response to the fuel shortages of the early 1970s, MTO, in co-operation with the federal and provincial energy ministries, sponsored three alternative fuel transit bus demonstrations. These demonstrations were held in the 1982 – 1989 period in Ottawa, Hamilton, and Mississauga. The Ottawa demonstration probed the viability of propane as a transit bus fuel, while the Hamilton and Mississauga demonstrations dealt with natural gas.

The mid-80s brought a new challenge to the transit industry: the reduction of diesel engine exhaust emissions of particulates (smoke) and oxides of nitrogen. In 1985, the U.S. Environmental Protection Agency (EPA) proposed stringent technology forcing emission standards for introduction in the 1991 – 1994 time frame. The transit bus was singled out by the EPA to be the test case for these standards. The bus was expected to meet, in 1991, the same standards that heavy-duty trucks have to face in 1994. However, the recently passed U.S. Clean Air Act postponed the introduction of the 1991 bus standard to 1993.

In 1988, MTO recognized society's growing concerns about diesel exhaust and sponsored a new and more comprehensive natural gas bus demonstration simultaneously at three sites: Toronto, Hamilton, and Mississauga. This program encompasses all major aspects of an alternative fuel application, viz., the vehicle, the fuel, and the infrastructure.

In the design, co-ordination, and monitoring of these demonstrations and many complementary projects, MTO staff gained extensive experience with alternative fuels and their application in transit buses. Given the widespread interest in alternative fuels and the uniqueness of our experience, it became worthwhile to prepare this report – *Assessment of Transit Bus Propulsion Options in Ontario*.

The report discusses the technology and economics of clean diesel, methanol, natural gas, propane, and electric trolley buses in individual chapters. At the end of the report, the economics and environmental and social impacts of these alternatives are compared in two additional chapters.

Before the results of this study are presented, it is worth noting that we are dealing with a rapidly evolving subject. The analyses and even the conclusions of this report may be subject to revision in the years to come.

In what follows in this summary, the status of each alternative is described individually. This is followed by a comparison of the alternatives with respect to their environmental and economic impacts.

Clean Diesel

Clean diesel refers to a combination of diesel fuel and diesel engine which, when tested on the EPA transient heavy-duty test cycle, meet the 1993 transit bus engine standards. The 0.1 g/hp-h particulate level is the most difficult standard to meet, and today there is no production diesel engine that meets this level without a particulate filter and low-sulphur fuel (less than 0.05 %wt sulphur content).

Most diesel engine manufacturers are engaged in intensive engine development programs to reduce soot formation in their engines. Extremely high pressure injection systems, much refined oil control systems, improved injector tip and combustion chamber designs, electronic engine and transmission controls, and variable geometry turbochargers are some of the means implemented by many engine suppliers. At present, well-designed engines meet the 0.25 g/hp-h truck engine standard; however, in the short term, engine refinement alone may not suffice to meet the 0.1 g/hp-h standard with sufficient margin to compensate for deterioration over the 464 000 km (290 000 mile) EPA durability cycle. In the long term, it is conceivable that some engine manufacturers will meet this standard without a particulate trap.

Thus, in the 1992 – 1993 time frame, diesel engines may have to be equipped with particulate traps and run on low-sulphur diesel fuel. The aromatic content of the fuel may also be limited to 10 %v, as will be the case in California starting in October 1993.

At present, the reliability of particulate trap systems is not known. The fact that it is necessary to regenerate traps gives rise to significant complexity and potential failure modes. The cost of the particulate trap is not established either. Most engine manufacturers predict that the particulate trap equipped clean diesel will cost approximately twice as much as the corresponding regular diesel. This would imply a capital cost premium of approximately \$10 K. In addition, the maintenance and fuelling costs of this engine will be significantly higher than those of the regular diesel engine. The annual maintenance cost premium is estimated at approximately \$750, while the fuel price

premium for low-sulphur fuel is predicted to be 3 ¢/L. Particulate traps result in a small fuel consumption increase, which is estimated at 2 – 5%.

In summary, the particulate trap technology is far from established. The reliability and cost of particulate traps remain rough estimates.

The New York City Transit Authority has placed a 400-bus order in which particulate traps are specified. Detroit Diesel Corporation (DDC), Donaldson Company Inc., and Transportation Manufacturing Corp. (TMC) are co-operating in the delivery of this order. This program will undoubtedly expedite the development of the clean diesel option.

Many transit operators prefer the clean diesel option, because it requires the least change from present operating practices. In addition, it does not necessitate any significant additional infrastructure costs.

The long-term acceptability of the mature clean diesel is, however, far from assured. The health effects of its exhaust may still be unacceptable, because of the carcinogenicity of some of its components such as polynuclear aromatic hydrocarbons (PAHs).

Natural Gas

Natural gas is an abundant Canadian resource, which could potentially meet a large fraction of our transportation fuel requirements. Currently, 24 000 Canadian light- and medium-duty road vehicles are powered by natural gas.

Its high octane number, clean-burning characteristics, lower price, and wide availability in urban centres, make it an attractive spark-ignition engine fuel. Unfortunately, its gaseous state with the resulting low volumetric energy density is a major impediment to wider adoption. In order to mitigate this difficulty, natural gas is either compressed or liquefied for transportation usage. Compression and on-board storage at 20.7 MPa (3000 psi) is the primary method of utilization. However, even at this high pressure level, vehicles have to accommodate four to five times the diesel fuel capacity to assure the same range. The weight of the storage tanks (high-strength cylinders) and the cost of compression are areas in which improvements would be beneficial.

Currently, a number of transit engine and bus suppliers are actively developing products that will satisfy the rising demand for natural gas powered buses and meet the 1993 and 1994 exhaust emission standards. Some engine manufacturers have opted for throttled spark-ignited engines (e.g., Cummins and IVECO) and others for unthrottled compression-ignition engines (e.g., Detroit Diesel Corporation). Natural gas combustion inherently leads to very low particulate (soot), CO, and non-methane HC emissions. NO_x emissions, on the other hand, require either very lean operation, which is the technologically and economically preferred method, or the application of pollution control equipment.

Methane emissions, although of no consequence to human health, contribute to the greenhouse effect and will be effectively eliminated by the use of oxidation catalysts.

Whilst adequate durability and reliability data are not yet available, it is safe to predict that a number of engines meeting the most stringent standards and satisfying transit industry requirements will be available in the 1991 – 1992 time frame. The development of light-weight cylinders is also under way.

The efficient and safe utilization of natural gas in the transit environment calls for special attention to the fuelling, storage, and repair facilities of natural gas powered buses. Fuelling can be carried out either one bus at a time (fast filling), as is the case with diesel buses, or with all buses in the fleet simultaneously (slow filling). In both cases, sufficient compression capacity must be installed to deliver the required amount of gas within the typical eight-hour period in which buses are available for fuelling. The fast filling alternative is most compatible with present transit industry practices; however, it requires more elaborate and expensive fuelling station equipment.

The propensity of high pressure natural gas to leak must be accounted for in the design of buses as well as bus storage and repair facilities. While it is difficult to ignite and even more difficult to explode natural gas air mixtures in an unconfined environment, the same is not true in confined sites. Therefore, a higher standard of ventilation, hazard control/detection, and emergency response capability are prudent for bus garages housing natural gas powered buses. Needless to say, outdoor bus storage makes most of these precautions unnecessary.

At present, natural gas is not taxed at the provincial or federal level. This contributes greatly to its price advantage. Major natural gas contracts in Toronto are currently running at 10 to 12 ¢/m³. The electricity cost of natural gas fuelling stations is estimated at 1.5 ¢/m³. The resulting 11.5 to 13.5 ¢/m³ cost is less than half of that of the diesel fuel, on an equivalent energy basis. Thus, to transit systems natural gas offers a significant operating cost benefit. However, there are offsetting increases in capital expenditures. The bus price is expected to carry a \$34 K premium with the provincial tax concession and \$53 K without it; the fuelling station cost per bus is in the range of \$20 to \$24 K; and the additional cost for a new modern garage is estimated at \$4 K per bus. Furthermore, an increase in the maintenance cost of buses and facilities has to be accounted for. The net effect of these benefits and costs is best determined by life-cycle cost analysis, the results of which are presented at the end of this summary.

Methanol

Methanol is the simplest synthetic fuel suitable for automotive application. It can be made from a variety of feedstocks including coal and peat; however, the feedstock of choice today is natural gas. The current production of methanol is geared to satisfy the

needs of the chemical market; and new plants would be needed for methanol to capture a significant portion of the conventional fuel market.

The high octane number, relatively high energy density, liquid state, and clean burning characteristics make methanol a desirable alternative fuel, especially in spark-ignited engines. Consequently, many methanol demonstrations have been staged primarily with light-duty but also with heavy-duty vehicles (transit buses) in Europe, California, and Canada.

In North America, the development of methanol transit bus engines has been spearheaded by DDC, who started to work on methanol engines in 1980 and initiated the first North American methanol bus demonstration in 1984. Early DDC methanol engines (6V92TA) were plagued with poor reliability, high aldehyde and methanol emissions, and rather high operating costs. However, most recent improvements in fuel and oil additives as well as engine componentry appear to have helped overcome these difficulties. This engine meets the stringent 1993 EPA standards and is now undergoing the durability testing necessary for certification. DDC plans to market the engine widely in early 1991 at approximately double the price of the corresponding diesel engine. An oxidation catalyst is also in preparation; it could help the methanol engine to meet the emission standard with a comfortable margin.

Methanol's modest gains in the bus market are largely due to the widely known technical difficulties with methanol engines. However, there are additional contributing factors. The price of methanol has been volatile and rather high. The methanol industry maintains that this situation will change if and when methanol becomes an accepted fuel and is produced and shipped in large quantities. Health and safety concerns have been also raised. The toxicity, volatility, and poor flame visibility are the major concerns.

It is difficult to assign a market value to methanol. Therefore, a price range of 14¢ to 21¢ per litre is estimated in industry and government reports. Noting that 2.5 to 2.8 litres of methanol are needed to replace one litre of diesel fuel, the diesel equivalent cost of methanol would range between 35¢ to 59¢ per litre. Thus, even in the best scenario, methanol is not cheaper than diesel fuel under current conditions. Methanol bus prices have not settled down yet, but in a mature market a premium of \$14 K with the sales tax concession and \$31 K without it is expected. The use of methanol will also call for additional capital expenditures for fuelling stations and garage modifications. The cost of fuelling station and garage modification are estimated at \$4 K per bus each. The K per maintenance costs of the bus and facilities will also carry a significant premium.

Propane

Propane, after gasoline and diesel fuel, is the third most commonly used automotive fuel in Canada. At present, more than 150 000 Canadian light- and medium-duty vehicles are run on this fuel. It is a by-product of natural gas and petroleum refining, and, if the

entire Canadian production were diverted to the transportation sector, it could power up to 10 – 15 % of our automotive fleet.

Its high octane number, clean-burning characteristics, and relatively high energy density make propane a desirable spark-ignition engine fuel. Furthermore, it is widely available in Ontario, its average historical price has been highly competitive, and it requires a relatively inexpensive fuelling station.

Unfortunately, there are few heavy-duty propane engines that can be readily integrated into common North American bus designs. The Ottawa propane bus demonstration had to resort to IVECO demonstration engines, which, due to their state of development, could not produce adequate reliability. The exhaust emission levels of this engine also left much to be desired. Particulate emissions, as expected from a spark-ignition engine, were very low. However, NO_x and CO emissions were higher than those of standard bus diesel engines. Clearly, further engine development and emissions control equipment are necessary to meet pending emission standards. Whilst this does not appear to be an insurmountable task, it will require significant resources and time to accomplish.

In contrast, the utilization cost of propane may be acceptable. At present large propane users pay approximately 20.3 ¢/L for propane. This is a highly attractive price. However, a number of factors mitigate this advantage. The volumetric energy content of propane is only 70% of that of diesel fuel. In addition, throttled and spark-ignited engines, which currently represent the best propane engine technology, are approximately 10% less efficient than typical diesel engines under transit bus operating conditions (due to very long idle periods). The somewhat higher weight of propane storage tanks adds a further efficiency penalty. Due to these and other minor operational inefficiencies, mature propane buses may consume approximately 60% more fuel than diesel buses. This would imply a diesel equivalent fuel price of 32.5 ¢/L. The purchase price of propane ¢/L buses is expected to carry a premium of approximately \$14 K with the provincial sales tax concession and \$31 K without it. Other major cost considerations include higher infrastructure and maintenance costs.

Despite the fuel cost advantage, propane has not been able to break into the Canadian transit bus market. The lack of reliable heavy-duty propane engines is one of the primary reasons for this failure. Other contributing factors include lack of adequate overfill protection systems to allow routine indoor bus storage and maintenance, and inability by the propane distributors to stage a co-ordinated development and promotion effort. Temporary yet large fluctuations in propane prices in response to high demand episodes have also dampened the enthusiasm of potential propane users. However, if and when its supply, pricing, and technology are assured, propane may become a viable transit bus fuel. The fact that the entire Vienna transit bus fleet is run today on propane may be sufficient evidence for this prediction.

Electricity

Electricity is a form of energy rather than an alternative fuel. However, it can be produced economically from a wide variety of hydraulic, nuclear, and fossil sources. In fact, a large number of transportation vehicles run on electricity today. These include above-ground trains, subway trains, streetcars, and trolley buses. The electric vehicle that comes closest to being an alternative to the diesel bus is the electric trolley.

Electric trolleys produce no exhaust emissions at the point of use and very low noise levels. However, they do produce emissions and hazardous waste at the generating station. Given that Ontario's hydraulic sources are limited, additional electricity has to be generated using either nuclear or fossil sources, which have their associated environmental problems.

The electric trolley technology is well established. Standard trolleys, which run solely by an overhead system, as well as more advanced trolleys with various degrees of off-line capability are available. Dual-mode trolleys, which can run long distances either on diesel fuel or electricity, offer great versatility. However, there is a large capital and operating cost premium to be reckoned with.

The necessity of building and maintaining an expensive overhead system and associated transformer stations is a disadvantage of trolleys. Lack of flexibility in assigning vehicles to various routes and lack of manoeuvrability are significant considerations for transit operators. The dual-mode bus is the industry's response to this concern. Repair, maintenance, and storage facilities for trolley buses are also somewhat more elaborate and expensive.

It is difficult to assemble representative capital and operating costs for trolley systems. Only nine North American transit systems are operating trolleys in significant numbers. MTO has commissioned a study to assemble the available data on these trolley systems. The results indicate that a standard trolley bus with only a limited off-line capability (a light-duty diesel engine) would cost \$427,000 (with no provincial sales tax), more than twice as much as the diesel bus. The overhead line cost, including the transformer substations, is estimated at \$1.53 million per two-way route kilometre, which is an additional cost to be dealt with. These overhead data were obtained from the Toronto Transit Commission (TTC) because it was felt that the costs from other cities depended on local conditions.

In view of the large capital cost premiums, trolley buses are not expected to gain widespread use. However, they may be accepted in certain locations, where operation over hilly terrain with large gradients or operation through tunnels is required.

Environmental and Social Impacts

A major impetus for considering alternative fuels for transit buses at the present time is the obvious negative environmental impacts associated with the continued use of diesel fuelled buses as they are currently designed. Prominent among these are visible smoke, odour, and noise, all of which are particularly objectionable in urban environments. Starting in 1991, all new engines used in transit buses will have to meet progressively stringent new standards. The engines that are eventually supplied will use either upgraded diesel technology or rely on alternative fuels.

Although common or very similar standards will be met by all alternatives, the amounts of regulated pollutants actually emitted will vary from fuel to fuel. Furthermore, there will be even greater differences in the amounts of unregulated emissions and, therefore, in the reactivity of the exhaust of each alternative. The reactivity, after all, is the best indicator for gauging the physiological effects of a substance.

Clearly, electric trolleys have no significant emission of any pollutant at the point of use. However, fossil fuel powered generating stations produce pollutants while nuclear stations create hazardous waste. Over and above the pollutants produced by conventional buses, oil powered and, especially, coal powered generating stations produce substantial quantities of sulphur dioxide and fly ash. The amount produced depends on the type and quality of the fuel. In Ontario, the fuel source for generating electricity is: nuclear 50%, hydraulic 25%, and fossil 25%. The fossil energy sources are used to generate peak power, as required.

Trolleys were considered for transit use in the 1960s and 1970s to eliminate the soot and other pollutants generated by the use of diesels. However, the introduction of modern diesels and alternative fuelled buses is significantly reducing emissions of soot and other pollutants. Consequently, the environmental benefits of introducing trolleys today are not as great as in the past.

It is difficult to directly compare the impact of the emissions produced at the generating station with that produced by the bus locally. However, an indication of the relative magnitudes of emissions from various transportation sources can be obtained by comparing the daily kilometres travelled each day by buses, cars, and trucks. Taking Toronto as an example, daily travel in Toronto amounts to approximately 360 000 km by buses, 38 500 000 km by cars, and about 8 600 000 km by trucks. Of the total NO_x and volatile organic compounds (VOCs) produced by ground transportation vehicles, buses account for approximately 2.7% and 0.6% respectively. Modern diesel and alternative fuelled buses would reduce the NO_x contribution to approximately 1.5%. Approximately 6% of the current bus fleet is made up of trolley buses. Replacement of these trolley buses by clean alternative fuel buses would result in increases of urban NO_x and VOC emissions of 0.09% and 0.04% respectively, even assuming that no emissions whatsoever are produced at the electrical generating stations. When these emissions are included (see Table 33), the differences between trolley buses and other buses

become negligible, except that fossil-fuelled electrical generating stations produce significant amounts of sulphur dioxide.

Apart from exhaust emissions, toxicity and fire hazards are important considerations. With respect to toxicity, natural gas and, to a lesser extent, propane are superior to the reformulated diesel and methanol. With respect to fire hazards, diesel fuel is deemed to be superior to methanol, propane, and natural gas.

Global effects are of growing importance. Specifically, concern with the greenhouse effect and acid rain is gaining momentum. All alternatives, with the exception of electricity from hydraulic and nuclear sources but including electricity generated from fossil fuels, contribute to the greenhouse effect. Recent studies show that coal generates 25-50% more CO₂ than petroleum-based fuels, while natural gas generates 8-19% less. Sulphur and NO_x emissions contribute to the acid rain problem. Again, electricity from hydraulic and nuclear sources is not a contributor, but all the other alternatives are, with the diesel being probably the worst alternative for NO_x.

Water pollution and surface contamination are additional concerns. Liquid fuels are clearly inferior to gases in this respect. Natural gas is probably the most benign alternative.

In conclusion, each alternative poses unique health, environmental, and safety concerns.

Economic Impacts

The full-scale adoption of alternative propulsion options will have wide-ranging economic ramifications, which are, at present, not fully established.

In this study, we have attempted to estimate the life-cycle cost impact of each alternative relative to that of the 1989 diesel bus at a common operational, environmental, and safety standard. The operational standard is set by the present diesel experience; the environmental standard is dictated by the proposed 1993 bus exhaust emission standards; while the safety standards are set by a combination of regulatory requirements and present transit norms in Ontario. The results of this economic analysis are rather sensitive to some of the underlying assumptions adopted, which are explained below.

The most significant cost items specific to the propulsion option are the price of the fuel or energy and the capital cost of the bus and all necessary infrastructure elements, fuelling station, garage, and overhead system (for electric trolleys). Service and maintenance costs may also vary among the alternatives, but these differences constitute second-order effects with fully developed alternatives.

The average price of the 1989 diesel fuel (baseline case) for Ontario transit systems was 37 ¢/L. This price includes a provincial sales tax of 10.9 ¢/L. The 1990 price of the low-sulphur diesel is estimated at 40 ¢/L and that of the reformulated diesel at 46 ¢/L. These estimates are based on petroleum industry and U.S. government predictions, which assume a constant price for crude oil and attempt to account for additional refining and distribution costs.

The price of natural gas is set by long-term contracts between large users and suppliers. The present price paid by TTC is 12 ¢/m³, which is the basis for our assumption. A further 1.5 ¢/m³ is added to this price to account for the average energy cost of compression to produce compressed natural gas.

The price of propane for large-scale users with long-term contracts is running at approximately 20.3 ¢/L in Ontario (as of June 1990). This price includes a provincial sales tax of 4.3 ¢/L.

The price of electricity for the largest trolley bus operator in Ontario, TTC, is currently 6.6 ¢/kW-h.

Methanol is used primarily as a chemical feedstock rather than an automotive fuel. Therefore, the future price of fuel-grade methanol has to be estimated. Industry and government sponsored reports, which have analyzed the production cost of methanol from natural gas in various parts of the world, conclude that the price of fuel-grade methanol would be in the 14 to 21 ¢/L range. The price adopted in this report is 16.7 ¢/L.

The fuel and energy efficiency of buses is another crucial parameter influencing the fuelling cost of each alternative. The diesel and trolley bus efficiencies are well established, while those of the alternative fuels are derived from the demonstration data accumulated in Ontario and other jurisdictions.

The price of the baseline 1989 diesel bus is \$186,000, a number which represents the average price paid by Ontario transit systems in 1989. The \$202,000 price of the 1991 diesel is an estimate, which includes the cost of the particulate trap and an upgraded diesel engine. The prices for the natural gas, methanol, and propane buses were estimated by accounting for the inherent cost of the new engines and fuel storage systems. The resulting prices are \$200,000 for the methanol and propane buses and \$220,000 for the natural gas bus. It should be noted that some prototype alternative fuel buses have been purchased at higher prices, which reflect the relatively high development costs. The \$427,000 electric trolley bus price was established in an independent consultant's report, which included a survey of most recent North American purchases. At present, the alternative fuel buses, including the electric trolley, are exempted from the 8% provincial sales tax. This fact has been accounted for in establishing the prices mentioned above.

The additional or incremental infrastructure costs, viz., costs that have to be incurred above and beyond those incurred by typical diesel fleets, are significant for some of the alternatives. Natural gas, methanol, and propane necessitate the installation of new fuelling stations and improvements to the garaging facilities to mitigate the hazards of dealing with more volatile fuels. In the estimation of these costs, a typical garage handling 250 transit buses has been considered.

The fuelling station costs on a per bus basis are \$24 K for natural gas, \$4 K for methanol, and \$2 K for propane. These figures are based on the recent experience gained in Ontario and other North American jurisdictions. With indoor bus storage, the cost of garage improvements is estimated at \$4 K per bus for methanol, natural gas, and propane. This estimate represents the incremental cost of building a new garage to accommodate alternative fuel buses. The introduction of new electric trolley lines necessitates a new overhead system and transformer substations. The installation cost of these is estimated by TTC at \$1.53 M per route kilometre. The present practice in Toronto and Hamilton results in 1.7 buses being allocated per route kilometre. This figure includes 10-12% spare units. Thus, the overhead system cost on a per bus basis amounts to \$926 K. However, this and most other infrastructure elements have a longer useful life than the bus itself. This fact is recognized in our economic analysis by assigning an appropriate residual value to the incremental infrastructure costs at the end of the bus life.

The incremental bus and infrastructure maintenance costs of the alternatives are quantified in this report as well. However, these are only estimates that attempt to predict inherent differences, rather than those experienced at present with prototype units.

The above facts and figures are integrated in a life-cycle cost analysis model, which was developed at MTO for this specific project. The analysis sums up all incremental costs in 1990 dollars relative to those of the 1989 diesel bus over an 18-year life cycle. During this period, a typical Ontario transit bus runs 1.2 million service kilometres. In its earlier years the bus is used more extensively than in its later years. This fact is incorporated into the life-cycle cost analysis program. All costs are brought to their present values by employing a discount rate of 5%, which represents the net effect of interest rates and inflation.

A representative model prediction is provided in Figure 25 on page 85. This figure includes six alternatives: 1991 diesel bus running on clean diesel, natural gas, methanol, propane, and electric trolley buses (two options). The results indicate that all alternatives except natural gas will introduce a cost penalty relative to the 1989 diesel. The penalty in dollars per 100 km of revenue service amounts to approximately \$3 (propane) to \$53 (electric trolley with overhead).

The magnitude of the results are sensitive to the estimates adopted and assumptions made in the study. However, an extensive sensitivity analysis testing our estimates and assumptions, such as various taxation scenarios, indicates that the relative ranking of the fuels is not likely to change.

CONCLUSIONS

- 1/ Natural gas, methanol, propane, and clean diesel offer the potential to meet the environmental challenges of the 1990s. However, each of these alternatives will require more in-service evaluation to completely assess its characteristics against the traditional diesel bus. Trolleys can also meet the environmental challenges, provided the electricity is derived from non-polluting energy sources.
- 2/ The alternative fuel demonstrations in Ontario and elsewhere are the only major contributors to the development and evaluation process, which may help to establish objectively the operational and cost parameters of the alternative fuels. These efforts should be continued.
- 3/ The life-cycle cost analysis presented in this report draws upon the best technical and economic data available in North America. The tentative conclusions of this analysis are that, among the six alternatives considered, natural gas has the smallest life-cycle cost and the electric trolley the largest in medium to large transit systems. Technological developments are not expected to change this conclusion.
- 4/ The development and introduction of alternative fuelled buses and modern clean diesel buses offer significant reductions in pollutants and soot and are capable of meeting the stricter 1991 and 1993 emission standards. From an overall perspective of energy security, environmental impact, economy, and operational flexibility, these buses should be considered when planning any bus route. Trolleys do not emit pollutants at the point of use, and hence will also meet the stricter 1991 and 1993 emission standards. However, peak period trolley service does lead to the generation of pollutants and hazardous waste materials at power plant sites. The environmental benefits of introducing trolleys rather than modern diesels or alternative fuelled buses are not as great today as in the past. In a typical modern city where trolleys account for 5-7% of the bus fleet, the effect on the environment from using alternative fuelled buses rather than trolleys is approximately 0.09% more NOx and 0.04% more VOCs.

1/ INTRODUCTION

Diesel fuel and diesel transit buses have come under stricter scrutiny in the last few years. Their impact on air quality and noise are a major concern in large urban centres. Furthermore, the contribution of diesel combustion to the greenhouse effect is becoming an important issue. These new issues have overwhelmed the topics of the energy crisis era: namely, the long-term availability, quality, and cost of diesel fuel. However, the transit industry must remain sensitive to all of these developments.

The diesel engine provides a high level of reliability at a relatively low capital and operating cost, which is very difficult to match with electric propulsion systems or alternative fuel engines. However, the introduction of increasingly stringent exhaust emission standards, in the U.S. and Canada, will substantially increase the capital and operating costs of the diesel transit bus and erode some of its advantages. In addition, certain jurisdictions may even ban the purchase and operation of new diesel buses. Therefore, it is highly pertinent to systematically and objectively evaluate the alternatives to the diesel engine.

This MTO study, Bus Propulsion Options, was designed to review periodically the status of major bus propulsion system options. It is understood that many factors affecting the status of each option will be changing, especially during this period of intense regulatory and technical activity. Therefore, the specifics of the present report should be considered a snapshot of the current state. However, the methodology and fundamentals should be valid for a longer time.

The propulsion options considered in this report are:

- Diesel
- Methanol
- Electricity
- Propane
- Natural gas

The pros and cons of each option are discussed in detail, especially with respect to cost, safety, and environmental implications. Cost, apart from its usual significance, is a valuable performance criterion if it can be applied to bring each option to the same level of acceptability with respect to operability, efficiency, safety, and environmental impact.



2/ BACKGROUND

2.1/ Diesel Bus and Electric Trolley Experience in the Transit Industry

Diesel transit engines became popular in the early 1960s. At the time, diesel fuel was a less valued product of the petroleum refining process and much cheaper than gasoline. In addition, diesel fuel contains more energy per unit volume than gasoline, while the efficiency of compression ignition engines surpasses that of spark ignition engines. Thus, the diesel engine has enjoyed a solid economic advantage against its only credible competition – the gasoline engine.

Over the past 25 years, the Detroit Diesel 6V-71N engine has gained a reputation for reliability and durability second to none. Transit operators have routinely operated this engine 400 000 kilometres between major overhauls, with minimal preventive maintenance.

The first North American trackless trolley line was put into service in Colorado in 1897. Since then, more than a dozen North American transit systems have employed electric trolley buses. At present, only nine of these systems have active fleets. These include the Canadian transit systems of Toronto, Hamilton, Vancouver, and Edmonton.

2.2/ Social, Environmental, and Economic Issues Affecting the Transit Industry

Until recently, exhaust emissions from trucks and buses were not tightly controlled in North America. In response to health and environmental concerns, the U.S. Environmental Protection Agency (EPA) has proposed exhaust emission standards for trucks and buses, to be phased in over the next few years. The standards promulgated by the U.S. Clean Air Act of 1990 have been reproduced in Table 1, for reference.

Table 1/ Bus and Heavy-Duty Truck Exhaust Emission Standards

Exhaust Limit g/hp-h	Canada Dec. 1, 1988	U.S. 49 State Jan. 1, 1988	U.S. 49 State 1991 – 1992	U.S. 49 State Jan. 1, 1993	U.S. 49 State Jan. 1, 1994
C O	15.5	15.5	15.5	15.5	15.5
H C	1.3	1.3	1.3	1.3	1.3
NOx	6.0	10.6	6.0	5.0	5.0
PM*	0.6	0.6	0.25	0.1	0.05

* Particulate Matter

In Canada, the 1991 U.S. standards may be adopted with a time lag giving suppliers to the Canadian market extra time to meet the same standards. However, since the U.S. market absorbs 90% of total transit engine production, the emissions technology is driven by the U.S. market and will be available in Canada at the same time that it is in

the U.S. Therefore, a lag in adopting similar emissions standards in Canada will not provide any advantage to engine manufacturers and bus operators.

2.3/ Alternative Transit Bus Propulsion Options

A number of viable alternatives to the diesel engine in transit are currently under development. Fuels such as propane, natural gas, methanol, and electricity may soon provide reliable, cost-effective alternatives to the diesel dominated transit industry.

Engines fuelled by these alternatives would have to meet the same tough emission standards as the new diesel engines. The alternatively fuelled engine has two significant advantages over the diesel in meeting these standards.

The first is that the emissions control technology to do this has already been developed and has been in operation for years in light-duty automotive engines. For instance, catalytic converters and exhaust gas recirculation systems have been in use for more than ten years now for automotive gasoline engines.

Secondly, the emission control equipment that must be installed on a spark-ignited engine is, in general, cheaper than equipment under development for diesel engines. Even if the technical difficulties are overcome, the capital and maintenance costs of the clean diesel may render it uncompetitive when compared to spark-ignited, alternatively fuelled options.

2.4/ Ontario's Experience with Alternative Transportation Fuels

At the time this report was commissioned, the province was supporting three separate demonstrations in transit bus applications of alternative fuels (not including trolley bus operations). These demonstrations are shown in Table 2.

Table 2/ Ontario Transit ATF Programs

Transit Property	Demo Size/Type	Demo Date
Ottawa-Carleton Transpo	9 Propane buses	1982-1988
Hamilton Street Railway	6 Natural Gas buses	1984-present
Mississauga Transit	1 Natural Gas bus	1986-present

The Ottawa (OC Transpo) and Hamilton (HSR) demonstrations involved the conversion of older GMC 40-foot buses, built in the late 1970s. The buses had the Detroit Diesel Allison 6V-71 diesel engines replaced with IVECO 10.4 L in-line six-cylinder engines converted to propane and natural gas by DEREKO of Switzerland.

The engines were coupled to the V-730 transmissions through an adapter housing. Modifications were made to the cradle assembly to accommodate the new engine.

The IVECO engines were built to rotate in the same direction as the 6V-71 (which is opposite to almost all other transit engines in the world).

The OC Transpo propane bus had a manifolded propane fuel tank capable of holding 640 L of fuel. This tank provides the bus with a range in excess of 600 kilometres.

The HSR natural gas bus is equipped with a seven-cylinder fuel storage system. Each cylinder is constructed of aluminum, wrapped with fibreglass and is capable of storing approximately 30.7 standard cubic metres (1084 cubic feet) of natural gas at a pressure of 20.7 MPa (3000 psi). Total fuel capacity is therefore 215 cubic metres, providing a range of approximately 350 kilometres.

The Mississauga Transit demonstration involves a 30-foot OBI Orion bus with a Chevrolet 7.4 L (454 cid) gasoline engine converted to run on natural gas. This engine was coupled to a 600 series Allison transmission in a conventional T-drive configuration.

The bus is equipped with four 30.7 cubic metre aluminum/fibreglass cylinders, which provide a range of about 250 kilometres.

All three programs have demonstrated significant savings in fuel cost relative to conventional diesel buses. Reliability and maintenance costs have been reasonable considering that each is the first application of these particular engines in transit buses.

In 1988, Toronto, Hamilton, and Mississauga embarked on a new, joint, natural gas bus demonstration, which is being co-ordinated and supported by MTO. This demonstration involves the commissioning of 50 original equipment manufacturer (OEM) built natural gas buses and the necessary infrastructure to support them in three transit bus garages.

The considerable R&D and operational experience gained in this program will assist the transit industry and MTO to gauge the potential of natural gas as a transit bus fuel in a more comprehensive and accurate manner.

3/ TRANSIT BUS PROPULSION OPTIONS

3.1/ Diesel

3.1.1/ Characteristics and Availability

Diesel fuel is composed of a mixture of heavier hydrocarbon liquids, having a relatively low vapour pressure compared to the alternative fuels discussed in this report. Table 3 compares the properties of diesel fuel to those of the alternatives discussed in this report (propane, natural gas, and methanol) and gasoline, for reference.

Diesel fuel quality is primarily based on cetane number, aromatic content, and sulphur content. Cetane number is a measure of the fuel's ability to auto-ignite upon injection. Fuel with a high cetane number ignites quickly, resulting in a low rate of combustion pressure rise and peak pressure. An engine fuelled with a high cetane fuel will be quieter running, produce lower levels of particulates and hydrocarbons, and last longer than a comparable engine fuelled by a low cetane fuel.

Aromatic and sulphur content have an impact on the generation of particulate emissions. In addition, sulphur oxides created during combustion may form sulphuric acid. Bearings, cylinder liners, pistons, valves, and exhaust component life may be seriously compromised by burning high sulphur fuel.

3.1.2/ Supply Infrastructure

Diesel engines have been increasingly favoured over spark-ignited alternatives in trucks and buses for about the past 30 years. Diesel fuel consumption has accounted for an ever increasing share of total transportation fuel consumption over this period (Figure 1).

A large infrastructure to refine, transport, and sell diesel fuel exists throughout the world. Because of its availability, cost advantage, high energy density, and excellent safety record, diesel has been the fuel of choice in the heavy transportation industry.

3.1.3/ Future Supply and Quality

The future supply and quality of diesel fuel is one of the biggest concerns of diesel engine operators. The demand for diesel fuel relative to gasoline has increased steadily for at least ten years now, and it is no longer a less valued by-product of petroleum refining.

Since the traditional production ratio of gasoline to diesel fuel has changed so much, diesel composition has gradually included lighter hydrocarbon fractions which would have previously gone into gasoline.

Table 3/ Fuel Properties

Property	Diesel #1 ⁽¹⁾	Gasoline	Methanol	Natural Gas ⁽²⁾	Propane
Molecular Formula	C ₈ -C ₂₀	C ₅ -C ₁₀	CH ₃ OH	>95% CH ₄	C ₃ H ₈
Constituents (% by weight)	86 - 88 C 12 - 14 H	86 - 88 C 12 - 14 H	37.5 C 12.6 H 49.9 O	76 C 24 H	82 C 18 H
Molecular Weight	Mixture	Mixture	32	~16.74	44
Density Liquid (kg/L) Gas (kg/m ³)	0.825 - 0.850	0.735 - 0.765	0.793	0.698	0.51
Density As Stored (kg/L)	as above	as above	as above	0.175 ⁽³⁾	0.51 ⁽⁴⁾
Lower Heating Value (MJ/kg)	42.9	43.8	19.99	47.4	46.3
Lower Heating Value (MJ/L) (MJ/m ³)	36.0	32.8	15.8	33.1	24.7
Latent Heat of Vapourization (kJ/kg)	544 - 795	310 - 502	1110	520	458
Boiling Point (°C)	175 - 270	25 - 210	65	-162	-43
Autoignition Temperature (°C)	200 - 260	230 - 480	450	650	470
Theoretical Air Requirement (kg/kg)	14.5	14.7	6.4	17.2	15.6
Ignition Limit Vol % Upper in air Lower	6. 0.6	8.0 0.6	36 7	15 5	9.5 1.9
Octane Number Research Motor	<5 <5	90 - 100 82 - 94	106 - 110 92	130 105	112 97
Cetane Number	35 - 45	<5	<5	<5	<5
Flash Point (°C)	>40	<-40	11	Gas	<-40
Solubility in Water	Zero	Zero	Infinite	NA	NA

1 - Average value, "Diesel Fuel Quality and Effects of Fuel Additives", TRB Report, May 1984

2 - Pipeline Gas in Ontario

3 - Compressed to 3000 psig

4 - Liquified under pressure

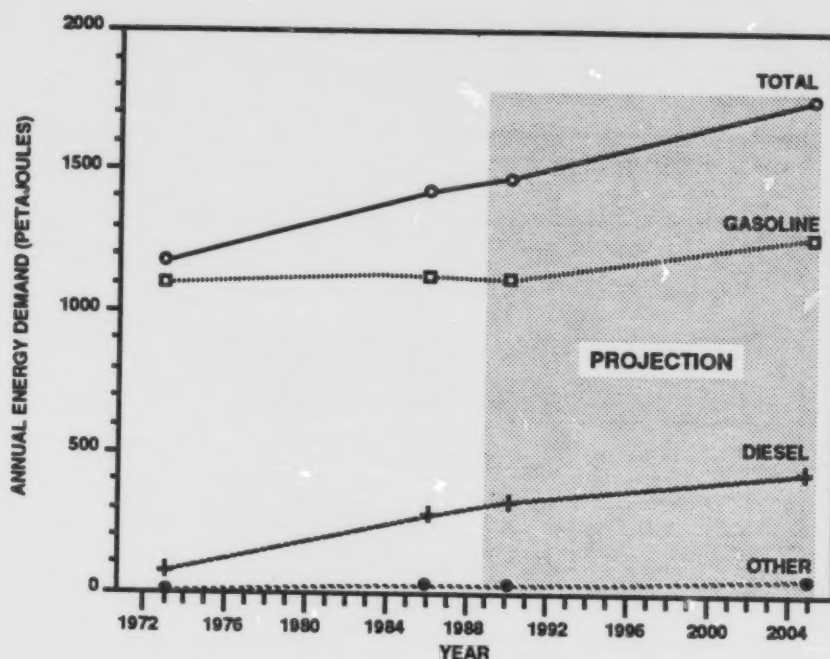


Figure 1 - Canadian Transportation Energy Consumption by Fuel [1]

In addition, the reduced demand for home-heating oil has left surplus components of high sulphur with a tendency to wax at relatively high temperatures, which must also be absorbed by diesel fuel production. The resulting fuel has reduced cetane number, higher aromatic and sulphur content, and a tendency to wax at higher temperatures.

The decreasing quality of domestic crude oil is also responsible for lower quality diesel fuel. Pumping from wells containing heavier crudes (as the higher quality wells are pumped out) and the introduction of alternative sources such as tar sands and oil shale (generally providing much lower quality feedstocks) results in fuels that are more difficult and dirtier to burn and harder on engines than those of the past.

North America consumes more energy per capita than any other part of the world. Existing sources of petroleum are rapidly being depleted and alternative sources are more expensive to tap. Dependence upon foreign sources leaves our industry open to unpredictable shortages and price increases.

The transit industry is very vulnerable to disruptions in fuel supply. It is also one industry that is almost entirely dependent upon diesel fuel to operate. One of the advantages of alternative fuels in transit is in the diversification of fuel sources, which could well provide protection from shortages and price volatility of traditional fuels.

3.1.4/ Diesel Engine Technology

Diesel engine manufacturers have made significant advances in past years, increasing specific power along with reducing fuel consumption and emissions. Oxides of nitrogen and particulate output have also been reduced significantly (Figure 2).

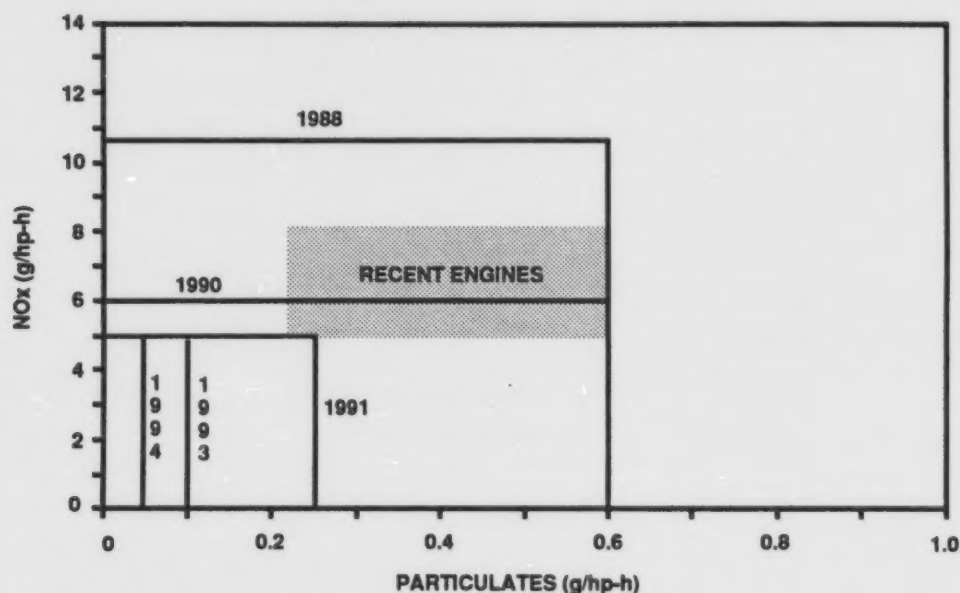


Figure 2/ Transit Diesel Emissions Relative to Standards

There is currently only a small number of diesel engines powering most North American transit buses. Most of these engines are produced by Detroit Diesel Corporation (DDC) and Cummins Engine Company. Specifications of transit bus engines produced by these two companies are listed in Table 4.

Table 4/ Common Diesel Bus Engine Specifications

Engine Model	Manu- facturer	Disp (L)	Max Power (kW)	Peak Torque (N.m)	Asp flg.	Config.	Mass (kg)	Max Speed (rpm)	Min BSFC* (g/kWh)
6V-71N	DDC	7.0	142	797	NA	V-6	889	2100	255
6V-92TA	DDC	9.1	201	1322	T	V-6	916	2100	206
L10-240	Cummins	10.0	179	1220	T	I-6	875	2100	198

*Brake Specific Fuel Consumption (BSFC)

The DDC 6V-71 was the North American transit engine of choice through the 1960s and 1970s, however this engine has been phased out in favour of the 6V-92TA (especially in the U.S.) due primarily to its greater power output and lower emissions. Cummins has only recently begun supplying transit bus diesel engines.

Although the power developed by most transit bus engines is modest, the 6V-71, 6V-92, and L-10 are relatively heavy compared to other truck engines. This alludes to the rugged operating conditions that transit engines must endure. A light-weight, medium-duty engine would not stand up as long. In addition, reliability and maintenance costs probably would not be acceptable to transit operators. Therefore, in selecting a candidate alternatively fuelled engine for transit, durability must be a prime consideration.

In order to meet past exhaust emission standards, diesel engine manufacturers have made gradual refinements to their engines. The pending EPA bus emission standards, however, require further, significant reductions in particulates and oxides of nitrogen, which may be beyond the limits of current technologies (Table 1). These same standards are also being considered for Canadian buses.

The main products of combustion from diesel exhaust are water, carbon dioxide (CO₂), carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), particulates, and aldehydes. The diesel exhaust emissions of greatest concern are NO_x, particulates, and aldehydes. The diesel engine produces relatively little CO and HC.

To satisfy the new emission standards as well as improve efficiency, durability, and noise, diesel engine manufacturers are concentrating their efforts in two areas. The first approach involves intensive refinement of engine parameters. Improved combustion processes and fuelling strategies enable cleaner, more efficient operation. Greater injection pressure and improved spray patterns promote better fuel mixing. Electronic injection controls, increased turbo boost pressure, and more effective aftercooling have also resulted in lower exhaust emissions.

Internal engine components are also undergoing significant development. Piston and ring design play a large part in the generation of soot from the consumption of engine lubricating oil. Improved combustion chamber design enhances atomization of fuel, which improves air utilization. Reduced injector nozzle sac volumes (injector tip end cavity) lower soot emissions by reducing residual fuel in the combustion chamber.

Variable geometry turbochargers, turbo-compounding, and tuned intake systems may improve engine transient response and further reduce smoke emissions during initial acceleration.

Improved metallurgy permits engines to operate at higher temperatures without damage, resulting in increased thermal efficiency. The use of ceramics in the production of internal engine components reduces the amount of heat rejected to the cooling system.

A second approach to cleaner diesel transit engines involves the installation of exhaust aftertreatment equipment. The most promising example to date is the particulate trap.

An exhaust trap contains a filter element that removes particulates from engine exhaust.

The element must be able to withstand high temperatures and must be sized so that it offers minimal restriction to exhaust flow as it fills. Most trap elements currently under development are composed of metallic screens or porous ceramics. Ceramic traps are currently under development in Canada, the U.S., Europe, and Japan. This configuration has the advantages of a heat resistant and compact structure. It may be manufactured on equipment similar to that currently used in the production of automotive catalyst substrates.

A typical ceramic trap consists of a ceramic substrate through which engine exhaust gases are passed (see Figure 3). The substrate consists of a matrix of parallel tubes configured very much like a honeycomb. One half of the tubes are closed at the inlet end and the other half closed at the outlet end. Pores in the tube walls allow gases to pass but collect particulate matter.

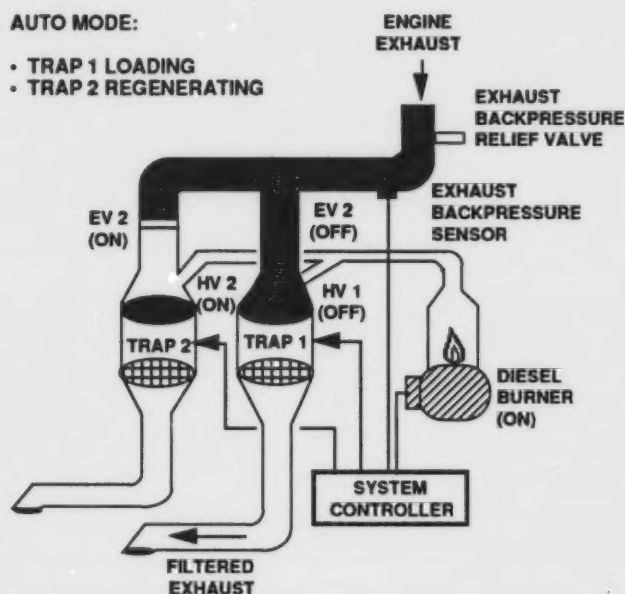


Figure 3/ Typical Ceramic Trap Assembly [2]

As the trap fills, back pressure on the engine exhaust increases. Increased back pressure results in reduced power output, poor driveability, and high fuel consumption. The trap must at some point be either replaced or cleaned out. Heating the trap element above the combustion temperature of the contained carbon (about 450°C) will cause the carbon to burn off. This process is called regeneration.

Initiating and controlling trap regeneration is not easy. Overheating the trap element may damage or destroy the substrate material. Insufficient heat or regeneration time will not completely clear the trap resulting in more frequent regeneration. The regeneration process is very difficult to control, once initiated. Much effort is currently being expended by engine manufacturers to limit regeneration temperature and improve temperature distribution in the substrate.

At present, a variety of means of initiating regeneration are being considered. One method uses engine exhaust gases to heat the element. Engine speed is increased to a predetermined level and the exhaust pipe partially restricted. This causes the trap element temperature to rise. Another means of initiating regeneration is through the use of an external diesel burner. Electrical heating of the trap is another possibility, which is at present gaining favour with most potential suppliers. Industry is developing many variants of these concepts, which have to be tested and refined in the years to come. Commercial availability is expected in the 1991-92 time frame.

Experience to date has not been encouraging. Frequent failures remain the norm rather than the exception. The use of traps to clean up diesel exhaust does not come without a price. The capital cost of a trap for a 150 kW engine is estimated at approximately \$10,000. In addition, the use of the trap will increase annual maintenance costs, fuel consumption, and possibly necessitate changes in bus operations to accommodate regeneration. It is expected that the trap core will have to be replaced every three to five years.

3.1.5/ Capital and Operating Costs

The diesel transit bus capital and operating costs are used as a baseline case for this report. Two scenarios are considered. The first is the total cost associated with the operation of a typical new (1989) bus and the second is the comparable cost breakdown for a diesel bus that satisfies future EPA emission standards.

While information for the first case may be estimated with some degree of accuracy from existing transit records, the second case involves a number of assumptions. The primary assumption is associated with the capital and maintenance costs of exhaust aftertreatment equipment. In addition, increased operating cost due to regeneration requirements of the buses and greater fuel cost of low-sulphur fuel and reduced efficiency of the "trapped" engine must be considered.

The cost estimates for the two scenarios are detailed below and summarized in Tables 5 and 6.

Table 5/ Diesel Bus Capital Cost

Description	1989 Diesel	Future Diesel
Bus (except engine)	\$156,815	\$156,815
Engine	\$ 15,000	\$ 20,000
Partic. Trap		\$ 10,000
Subtotal Bus	\$171,815	\$186,815
P.S. Tax (8%)	\$ 13,745	\$ 14,945
TOTAL	\$185,560	\$201,760

Table 6/ Future Diesel Engine Average Incremental Operating Cost

Description	Incremental Cost
Engine Maintenance	\$ 750/yr
Trap Replacement	\$ 333/yr
Reformulated Diesel Premium*	\$3,573/yr
Relative Fuel Economy	\$1,409/yr
TOTAL	\$6,065/yr

* Low sulphur fuel premium is estimated at \$1,190/yr.

A change in the exhaust emission regulations governing transit buses went into effect on December 1, 1988. While the DDC 6V-71N engine could still be specified in 40-foot transit buses up to this time, the DDC 6V-92TA must now be purchased. The costs of the two engines differ significantly. The 6V-71N typically lists (manufacturer's suggested list price) for about \$15,000 while the 6V-92TA lists for \$21,000. A large-volume purchaser of engines (truck or bus manufacturer) typically may obtain a 25% discount on these prices.

A diesel transit bus engine satisfying the 1994 emission standards will almost certainly be equipped with a particulate trap. Preliminary estimates from transit diesel engine manufacturers indicate that the price of the trap-equipped engine will probably be double that of current diesels (i.e., \$30,000 total instead of \$15,000). Trap estimates to date are in the \$5,000 to \$15,000 range, hence the \$10,000 median price taken for the above example. Base engine price was increased to \$20,000 to cover increased warranty coverage exposure for 464 000 km (290 000 mi).

Diesel bus maintenance costs have been estimated at approximately \$23,000 per bus year for 1989. Maintenance cost for the future diesel bus has been estimated at about \$23,750 due primarily to the addition of a particulate trap with burner and control system. These components will require periodic maintenance and will slightly increase the incidence of failure of the engine.

In addition to the \$23,750 maintenance cost for the 1991 diesel, a periodic \$3000 expense may be expected at intervals of 400 000 km representing trap element replacement. Trap replacement occurs in years five and ten of the bus life profile.

A typical 40-foot diesel bus in Ontario travels approximately 66 700 km per year. At an average fuel consumption of 53.6 L/100km (5.25 mpg) the bus would consume about 35 810 L (7895 gallons) of diesel fuel per year. An annual fuel cost of \$13,250 per bus based upon 37 ¢/L diesel price (the provincial transit average for 1989).

With the use of the 6V-92TA DDEC and more efficient four-stroke cycle engines such as the Cummins L10, transit bus fuel consumption should decline over the next three years.

However, buses purchased after 1990 will probably burn more fuel because of higher engine power ratings and particulate traps. This, plus the extra cost of low-sulphur fuel (estimated at 3 ¢/L) required by the new engines, will increase fuelling cost.

3.1.6/ Equipment Availability

Diesel engine manufacturers, such as DDC and Cummins, have announced the availability and price of their engine offerings for the early 1990s [3]. According to these announcements, in 1991 bus manufacturers will have access to diesel engines that meet the 0.25 g/hp-h particulate standard but not the 0.1 g/hp-h standard. To achieve the lower emission levels, particulate traps will be offered starting in mid-1991. However, these trap systems are far from being fully developed and may call for a higher level of maintenance. The announced price of particulate trap equipped engines is approximately double that of standard diesel engines.

3.1.7/ Low-Sulphur and Low-Aromatic Diesel Fuel

Low-sulphur diesel fuel meeting the 0.05% wt standard is already mandated in California. The provision of this fuel in Ontario does not pose insurmountable difficulties. However, a 3 ¢/L price premium may have to be paid.

California has mandated the provision of low-aromatic diesel fuel by October 1993. The maximum aromatic content of this fuel will be 10% v. The provision of this fuel in Ontario is technically possible, yet somewhat more difficult. The cost premium is estimated at 5 – 7 ¢/L.

3.2/ Methanol

3.2.1/ Characteristics and Availability

Methanol (Methyl alcohol, methyl hydrate, wood alcohol) is the simplest organic compound that is liquid at ordinary temperatures. It is made synthetically in large-scale plants (2000 ton/day) using natural gas as a feedstock. In principle, it can be made from any carbon-containing material including coal, wood, peat, or lignite, the choice depending on cost and availability. In all cases the fuel source is partially oxidized with steam or air in a combustor/reactor appropriate to the material. The product is a "synthesis gas" consisting of hydrogen and carbon monoxide. The second stage is to react this gas mixture at high temperatures and pressures in a catalytic reactor to yield the methanol.

Methanol belongs to the family of organic compounds called, generically, "alcohols." It must not be confused with a different liquid, common alcohol (ethyl alcohol, ethanol) which is made by fermentation and is found in alcoholic drinks. Though the cheapest synthetic liquid fuel, methanol is not quite as cheap as conventional hydrocarbons at present for the same energy content. Even though the feedstock in Canada (natural

gas) is much cheaper than petroleum, a lot of the energy is lost in manufacture (about 40%). Nevertheless, as sources of conventional liquid petroleum fuels become scarcer and more expensive, methanol may become the eventual replacement for gasoline and diesel fuel because of its convenience in handling as a liquid and the wide variety of possible feedstocks that can be used for its manufacture.

Though, as a liquid, methanol's physical characteristics are closer to petroleum fuels than other available alternative fuels, many of its chemical and combustion properties are distinctly different. Unlike hydrocarbons, it is completely miscible with water. It mixes relatively well at high levels with gasoline, for example, M85 (85% methanol, 15% gasoline) is being used experimentally in some specially designed cars. At low concentrations, however, its mixtures with gasoline are sensitive to trace quantities of water contamination, and other components (co-solvents) are needed to make reasonably stable mixtures. Methanol does not mix with diesel fuel at all by itself but low-level mixtures of reasonable time stability can be made with the aid of special emulsifiers.

Because of its affinity with water and limited compatibility with hydrocarbons, methanol causes special problems in lubrication. It can remove the lubricating film from rubbing surfaces, such as cylinder walls, and prevent it reforming. In the bulk oil it will form an emulsion with reduced lubricating quality and at low operating temperatures it will not readily boil away because of its higher boiling point (65°C) and its high latent heat. Another potential problem is one of the combustion products (formic acid) which is quite corrosive to iron and can cause premature wear. All these areas are undergoing extensive research and satisfactory lubrication and engine durability are likely to be obtained eventually through proper oil formulation and engine design.

Methanol is significantly different from hydrocarbons in combustion properties. It contains less than half the energy content of an equivalent volume diesel fuel (1 L diesel = 2.28 L methanol) so it cannot be used straight in unmodified engines. However, if low-level mixtures are considered, it can be used in such engines with some detectable change in performance. Consequently, there are two strategies for using methanol. Used straight in specially modified engines, the potential substitution benefits may be great and even superior performance may be obtained, but at a considerable cost in engine changes. However, if low-level substitution is acceptable, few engine changes may be required but the substitution benefit will be small and performance may be degraded.

3.2.2/ Cost and Availability

Methanol is a bulk chemical commodity with worldwide production of approximately 18 million tons per year. Canada produces about two million tons, much of which is exported to the U.S. Though large, these quantities are completely dwarfed by the size of the petroleum market (e.g., gasoline: 25 M tons in Canada). Consequently, it is difficult to predict the eventual price of methanol when production levels have increased to make a significant inroad into the fuel market. Current prices are dominated by the business

cycle and the balance between supply and the demand for its traditional uses, mainly in the production of plastics and chemicals. The recent variation of methanol prices expressed in gasoline equivalent units and compared with gasoline is shown in Figure 4. At times when the volumetric price fell below that of gasoline, cases were reported of it being used indiscriminately and illegally to dilute gasoline by a few local suppliers in the U.S. No such cases were reported in Canada, probably because the market is entirely in the hands of large internationally based companies. In 1988 the price of methanol rose sharply because of the temporary shutdown of a major U.S. plant at a time of greatly increasing demand. This demand has been largely due to expanding production of the octane improver, methyl t-butyl ether (MTBE), as a replacement for tetra ethyl lead, which is being eliminated from gasoline throughout North America. Over recent months the price has declined somewhat as supplies have increased. This experience has shown that reliance on current price levels is misleading as a guide to the levels applicable in a mature methanol economy when large-scale production of a fuel grade product takes place and when distribution costs are factored over volumes comparable to the fuel market.

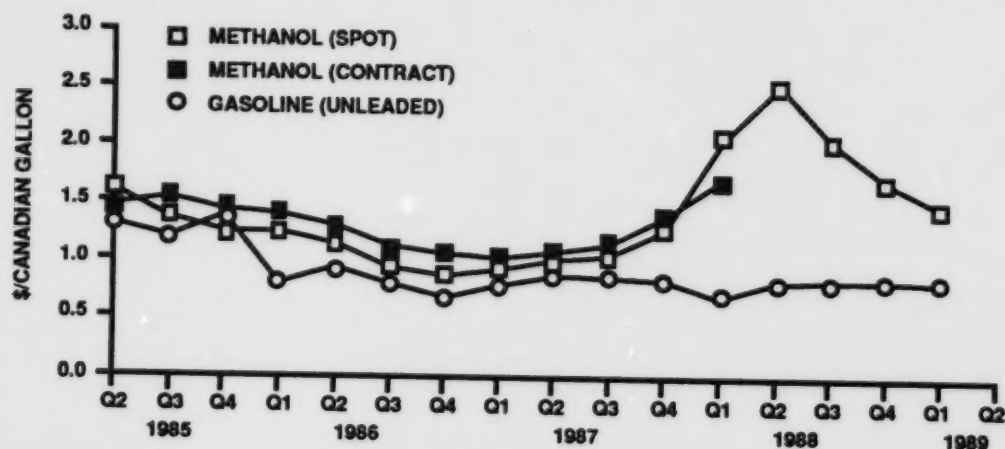


Figure 4/ Methanol and Gasoline Bulk Price [4]

The Canadian Oxygenated Fuels Association (COFA) has stated an interest in supporting the introduction of methanol buses in Ontario and the member companies have done so in demonstrations elsewhere. The price quoted by COFA for a proposed demonstration is \$0.20/L delivered; this is equal to 1.17 times the equivalent cost of diesel fuel on an equal energy basis. Prediction of future costs depends on the extent to which the fuel methanol market develops, principally in the U.S. In the very long term, methanol is predicted by many to become the liquid fuel of choice when conventional petroleum resources have become severely depleted. However, in the meantime, unless there are shortages of crude oil or large price increases, the growth of the market will depend on legislative action to meet air quality goals. Present volumes of chemical grade methanol are too low to make a significant contribution. A recent analysis [5] considers future scenarios in which much larger plants (up to 10 000 tons/day), involving new advances

in technology, make a fuel grade methanol less pure than the chemical product. Projected costs still depend on the sites chosen ranging from established gas fields, such as those of western Canada, to very remote locations such as the Arctic. Construction and operating costs are lowest for the fully established fields but the value of the feedstock gas is greatest there because of the ready distribution to developed natural gas markets. Conversely, the value of gas in remote locations is low but this is offset by the much higher construction and operating costs. The general prediction is that methanol costs will be a minimum for sites in between the two extremes, i.e., gas field locations which are close to industrially advanced areas but which do not yet export gas into large markets. The study identifies Mexico as the nearest site of this type in North America. This may have some significance in determining methanol prices to markets in the southern U.S. but probably not in Ontario, where feedstock costs in western Canada are of primary relevance. Cost predictions at site for these locations occupy a band from 0.109 to 0.127 Can\$/L.

COFA has supplied its own cost estimate of 0.103 CAN\$/L for large-scale plants in Alberta [6]. In 1988 it assumed a feedstock rate of 75% of the value given in a recent DOE report [5] which, when factored in, would increase the cost by about \$0.015/L thus bringing it into the middle of the report's prediction band, namely \$0.118. COFA also supplies estimates for the distribution costs amounting to \$0.048/L which brings the delivered cost minus profit to about \$0.166/L (possibly reduced by \$0.01 if the fuel is eventually pipelined). Though this is the best estimate so far, it is dependent on rather uncertain future developments requiring enormous commitments of resources and public policy. Caution should therefore be used in employing such numbers in life-cycle costing when compared with the costs of the traditional hydrocarbon fuels that are already available in assured quantities at Ontario locations.

3.2.3/ Supply and Handling

Extra costs in supplying and handling methanol at the garage will be incurred compared with diesel due to its flammability and increased bulk for equivalent performance. Its flammability is assumed to be equivalent to gasoline (Class I). Though gasoline has been used for buses in the past with little concern for possible risks, it is unlikely that a fuel of similar flammability could be re-introduced without significant modifications to alleviate safety and health concerns. Principally this would involve improved ventilation, new fire handling equipment, flammable vapour detectors, etc. With regard to ventilation at least, there is now such a need to improve air quality even in diesel garages. However, methanol fuelling has to be done outside like gasoline fuelling does and a separate fuelling facility will be necessary. The storage volume required should be about 2.5 times the equivalent diesel volume because of its lower energy density. The present Wilson garage has 2 x 45 000 L tanks (2 x 10 000 gals) which are refilled every two days so that the total methanol storage required would be about 225 000 L (5 x 10 000 gal tanks). All underground tanks now have to be double-walled to prevent seepage. Extra precautions when dealing with methanol may be necessary such as:

- Vapour recovery during bulk filling from supply tanker and during bus filling;
- Methanol resistant component materials, e.g., stainless steel or nickel plated nozzles, special hoses and pumps, etc.;
- Fine filters at the dispenser to remove contaminants, a particular problem with methanol;
- Dykes to contain fuel spills;
- Tank fuel level detectors or seepage detectors

There has been a rapid escalation recently in the environmental and safety requirements applying to the installation of underground fuel storage facilities. Small methanol facilities in the Methanol in Large Engines (MILE) program ranged from \$35,000 to \$50,000 for 1 x 10 000 gals in 1987 but these were single-walled steel tanks. More recently, a diesel facility at Hamilton Street Railway (HSR) comprising 4 x 10 000 gal + 1 x 5 000 gal tanks with three dispensers cost \$280,000. Discounting for two surplus dispensers and certain other charges, this would still be equivalent to about \$200,000 for a new methanol facility (or, indeed, a facility for any liquid fuel stored in underground tanks). Large increases in costs have arisen from the requirement for double-walled vessels and for fuel level or leak detection. Because of increasing legal liability for environmental contamination, insurance is becoming harder to get and it has been forecast that above ground storage may eventually be necessary for all liquid fuels.

3.2.4/ Technology Status and Developments

It is possible to use methanol in low concentrations to supplement diesel fuel, but this is unlikely to be considered for buses and will not be considered further in this report. For high concentrations, up to 100%, radical engine conversion is required. There are two methods: retention of the diesel cycle or conversion to an Otto cycle. There are pros and cons for both.

Retaining the diesel cycle means generally maintaining the existing performance characteristics, particularly low-load efficiency. The drive line match will also be retained at least in cases where it is the original or a compatible bus engine that is being converted. Maintenance practices will be similar with minimum retraining. Conversion to Otto cycle will cause many changes to performance, some of which will be improvements, e.g., higher output. Better exhaust cleanup strategies are available such as feedback control and three-way catalysts. However, conversion costs are likely to be greater with the need for large inventories of new components, e.g., ignition and carburetor parts. Engines may be less tolerant of field conditions that affect high voltage ignition. Engine cleaning practices will need to be checked.

Diesel Cycle Conversion

Because of its inherent high self-ignition temperature, methanol does not ignite readily by compression heating. This property may be obviated by several methods:

Heat Retention: Heat may be retained in the cylinders of two-stroke engines by lowering the scavenging ratio: the ratio of air blower capacity to cylinder pumping capacity. In practice this means that a larger proportion of hot exhaust gas is retained per cycle and the compression heating starts off from a higher temperature baseline. A similar effect could be induced, in principle, in four-strokes by exhaust gas recirculation (EGR). Retention of heat this way can be sufficient to enable compression ignition of even 100% methanol at moderate to high loads and when warmed up.

Ignition Sources: The usual ignition aid in a diesel is a glow plug. They are normally only used for starting at low temperatures and are not designed for continuous use. The current drain of conventional glow plugs is also very high and would cause an increased load on the alternator if used all the time. New types will probably need to be devised that act as ignition hot points maintained by combustion and catalytic effects and that need only intermittent electric heating. A spark plug may also be used as an ignition source (the "spark-ignited diesel"). However, it generally needs a different design than conventional gasoline plugs and its mode of voltage excitation has to be different. This is because, with diesel-like injection of the fuel into a large excess of air, combustion can only take place in locations where the lower combustion limit is exceeded. An extended spark period is needed to ensure combustion at all stages.

Ignition Improvers: The self-ignition quality of methanol may be much enhanced by cetane improvers. These compounds are generally organic nitrate esters – compounds formed by combining nitric acid with organic hydroxy-compounds. The excess oxygen in the nitrate grouping promotes combustion in a manner similar but less intense than found in explosives such as nitroglycerin, nitrocellulose, or PETN which are poly-nitrate esters with a large excess of available oxygen. Cetane improvers were originally developed to improve the quality of diesel fuel, for which only small percentages are needed (<1%). Much larger quantities are required to effect the same improvement with methanol (up to 15%) but newer materials have been synthesized which are more effective even at levels down to about 1 – 5%, e.g., some poly-glycol dinitrates and also a proprietary compound, Avocet (apparently mainly ethyl nitrate plus higher alkyl nitrates and other additives).

Some or all of these various techniques can be used in combination to convert engines to diesel cycle operation with methanol. Different manufacturers have adopted different strategies and Section 3.2.5 below lists some of the current developments to supply methanol burning engines for heavy-duty transport.

Otto Cycle Operation

The alternative is to convert a suitable engine to Otto cycle operation. Methanol has a high octane number and is inherently suitable for spark-ignition, homogenous charge combustion. High compression ratios can be used with, potentially, a higher power output and greater energy efficiency compared with gasoline.

The vapour pressure of methanol is low and the latent heat of evaporation is high. Without special design, this hinders starting ability at low temperatures. A simple remedy is to add other components to the fuel to increase volatility and a mixture containing 15% gasoline (M85) has become standard for use with a fleet of prototype passenger vehicles now being evaluated in North America. The high latent heat (about seven times as great as for an equivalent hydrocarbon combustion mixture) has varying effects. By absorbing more heat as it evaporates in the intake manifold, it lowers the charge temperature and increases the volumetric efficiency and power output. This is one of the main reasons for its use in racing engines. However the same absorption of heat makes early evaporation of the fuel more difficult during starting at low temperatures.

Other strategies have been used for spark-ignition engines to overcome some of the difficulties mentioned. It is possible to react methanol in a catalyst chamber to dissociate into combustible gases – hydrogen and carbon monoxide. These are more easily ignited in the engine and can give greater efficiency over part of the operating cycle. Another alternative is to vaporize the methanol with waste exhaust heat. Some of these techniques are described in the following section.

3.2.5/ Equipment Availability

The equipment described here is being developed or is already available from engine manufacturers and could be suitable for use in buses.

DDC Two-Stroke Engines

DDC manufactures a family of two-stroke engines, which are the most widely used in North American buses. Common in Ontario buses at present is the 6V-71 – a 7.1 L V6 with a Roots-type blower on the intake for scavenging. More common in the U.S. because of its higher output is the 6V-92TA – a 9.2 L V6 with a turbocharger and aftercooler ahead of the blower. The driving force for methanol engine development has been to meet air quality standards in the U.S., starting with California in 1984 and it is the 6V-92TA that has received the most attention. The turbocharger is an advantage in raising inlet temperatures to promote methanol self-ignition. Additional modifications have been made, including:

- Increased compression ratio
- Decreased blower flow rate
- Increased fuel flow
- Addition of glowplugs
- Control of blower bypass during transient operation.

Problems were originally encountered in ignition shut-down on coasting – caused by excessive cooling by the excess air flow. This is related to the design of the glow plug, which should be switched in as the temperature drops. Such problems would be more severe in Canadian climatic conditions. Converted engines have been already supplied for a demonstration in two locations in Canada under the Methanol in Large Engines project (MILE), the results of which are reported later in this section.

The performance of the 6V-92 has been reported by the manufacturer [7] and listed in Table 7. Emissions were calculated using the earlier 13-mode test – a weighted sequence of steady state measurements. Results cannot be compared directly with the EPA transient test cycle which new engines must now comply with. However, the comparison with diesel performance on the same test should be valid. CO was approximately 45-65% of the typical diesel version while NOx was only 25-45%. Particulates were 30-35%, though this is considered high for a methanol engine. It was probably due in this case to excessive leakage of lubricant into the airbox and it could be greatly reduced. Raw so-called hydrocarbons (actually, unburnt fuel, UBF, or methanol) show up two to three times greater than for the diesel but when allowance is made for the reduced carbon content and consequent propensity for smog formation, the numbers should be divided by two. Further improvements in the engine have shown much lower emissions; e.g., the particulates are about a third of the earlier value and this technology is believed by the manufacturer to be able to meet the 1991 standard.

Table 7/ MAN and Daimler Benz Methanol Engine Fuel Consumption and Emissions Performance

Engine	Fuel	Fuel Economy		Emissions (g/hp·h)						Comments
		lb/hph	mpig	UBF	HC	CO	NOx	PM	CH ₂ O ¹	
MAN D2566 FMUH (inc cat) [8]	Methanol		6.24	(0.85)		(0.33)	(8.10)	(0.04)	(0.084) ¹	EPA Bus Cycle [g/km]
MAN D2566 FMUH (inc cat)	Methanol	0.473		0.44	0.18	0.29	6.81	0.018 ²	0.046 ⁴	13 Mode Engine Test
MAN D2566 FMUH (inc cat) [9]	Methanol	0.537		0.68	0.05	0.31	6.61	0.043	<0.001	EPA HD Trans cold+hot
MAN D2566 FMUH (inc cat) [10]	Methanol			0.07		0.28	5.75	NA	NA	13 Mode Engine Test
MAN D2566 FMUH (inc cat) [10]	Methanol		6.35							ADB Cycle Road Test
MAN D2566 FMUH (no cat) [10]	Diesel		6.38							ADB Cycle Road Test
Daim. Benz M407hGo [11]	Methanol			0.39		5.36	3.90			13 Mode Engine Test
Daim. Benz M407hGo [11]	Methanol		4.84 to 6.28							Ave. on road for 3 buses with 245 000 km total

1 Formaldehyde

2 Total Aldehydes

3 7 Mode Test Only

The smaller 6V-71 engine, common in Ontario buses, has also been converted by the manufacturer. To make up for the lack of turbocharger heating, which assists the compression ignition of methanol, the engine is throttled over part of its range and uses blower bypass control to lower the scavenging rate. The methanol contained 2% castor oil for improved lubricity. This engine was higher in HC and CO than the larger engine while NOx was about the same. Great reductions in HC, CO, and also particulates were achieved with the use of an oxidation catalyst. However, the NOx was increased for reasons that have not yet been determined.

Since 1984, GM buses with 6V-92TA engines modified for methanol have been in service, first in the San Francisco area and then in other locations. Various aspects of performance have been reported including emissions, power output, fuel economy, and maintenance history.

Emissions were determined on a chassis dynamometer and quoted as gm/km rather than gm/hp.hr as defined in the standard [8]. However, the comparison with the diesel vehicle evaluated the same way shows the relative performance difference. The apparent HC was extremely high for methanol (30-50 times) though it consists almost entirely of unburnt fuel (methanol) and not hydrocarbons. Carbon monoxide was also very high (3-13 times) for the methanol case while NOx was reduced to 25-35% and particulates were reduced down to 8-25% of the diesel value. The extremely high values for UBF and CO seemed to be related to poor combustion control or misfiring particularly during idle and the low-load operation parts of the transient cycle.

Power output, as indicated by acceleration rates, was slightly less than for the diesel initially, resulting in about 2 mph less for the same period. This was due to, among other things, a time delay in the throttle mechanism. Subsequent improvements in the bypass blower control and fuel control have eliminated the difference. Fuel consumption at constant speed was similar for the two fuels – methanol varying between 2 and 6% more on a diesel equivalent (equal energy) basis. At idle, however, the fuel consumption of the methanol engine was much higher – partly as a result of a higher idle speed and increased electric load and partly because a richer fuel mixture is required at idle compared with diesel to ensure satisfactory firing.

Engine and component durability are continuing problem areas. Attention has been paid to all the fuel system parts as well as the internal surfaces affected by lubrication, and in-service modifications by the manufacturer have taken place. Earlier injectors failed due to insufficient lubrication and plugging. It is supposed that plugging is due to components in the lubricant, and over several component replacements, the service life has been extended. Likewise glowplug failure occurred frequently at first, due to overheating, but changes to the special 12-volt power controller have since reduced the problem. The reduced fuel pump life, caused by lack of proper fuel lubricity, has also been a problem. However, an analysis of engine oil for trace wear metals has not indicated any undue wear on internal engine components compared with diesel experience.

A joint industry/government sponsored program, Methanol in Large Engines (MILE) [12], to evaluate methanol fuelled vehicles, including buses, has been operating in Canada since 1986. Two buses each have been operated by Winnipeg Transit and by Medicine Hat Transit (Alberta), all powered by 6V-92 engines. Total accumulated distance on the four vehicles was over 320 000 km by November 1989. In service, the buses now consume methanol at a mean rate of about 2.6 – 2.7 times the volume of equivalent diesel buses which represents a relative energy efficiency drop of about 13 – 16%. It is claimed that overall reliability has improved since the beginning of the program due to a major upgrade of the engine. This includes the change to a fully electronic fuel management system (DDEC II) as well as new camshafts and cylinder liners. Starting is easier leading to the hope that glow plug life will be improved. Problems are still experienced with injectors, however, the configuration of which has changed from 8-hole to 12-hole and, lately, back again.

In another segment of the MILE program, an alternative strategy for adapting DDC engines to methanol has been adopted. To minimize conversion costs, an existing 8V-71 engine in a bus was modified to use methanol enhanced with the ignition improver, Avocet (mainly ethyl nitrate). The modifications required are fewer than for the use of straight methanol but include increasing the capacity of the various elements in the fuel line, e.g., pump, injectors, and fuel tank and replacing vulnerable elastomers and seals with methanol resistant components. The bus uses 7.5% Avocet and is in operation in shuttle service at Kennedy Airport, New York. Results have proved disappointing so far because emission levels were not much lower than for the diesel particularly smoke emissions, which arise from lubricant combustion. This may be due to the fact that old in-use engines were converted.

Since its introduction, the methanol 6V-92TA has undergone several modifications to improve performance and durability. Chassis dynamometer tests on buses incorporating several versions of this engine have been reported recently [13]. Fuel economy was greatly improved over the earlier 1984 version of the engine, and in one test showed a 25% greater energy efficiency over the diesel for the Central Business District (CBD) cycle. This may be due to an abnormally low reported fuel economy for the diesel in this particular test. Comparison tests over another type of city bus cycle (equivalent to the EPA Bus Cycle) indicated a more credible 4% decline in efficiency for the latest methanol bus compared to the diesel. Nevertheless, substantial improvements in efficiency had been gained overall with this engine translating into an equivalent fuel economy of 5.5 mpg. CO emissions were greatly reduced for the new engine to about one third of the levels for the diesel or the earlier methanol engine. NO_x was also reduced by about 30% from the previous engine. Organic emissions, chiefly unburnt methanol, showed considerable (30 – 50%) reductions with still further improvement with exhaust catalysts. However, these emissions were still a problem compared to the diesel. Likewise, particulate emissions, though still better than the diesel had not been reduced compared to the earlier engine. These arise from the combustion of engine oil, and further improvements in oil control are warranted. Since these tests, further changes have been made including a compression ratio increase to 23:1 which was intended to reduce

unburnt fuel and lower glow plug use. Figure 5 shows some fuel consumption and emissions data from this reference.

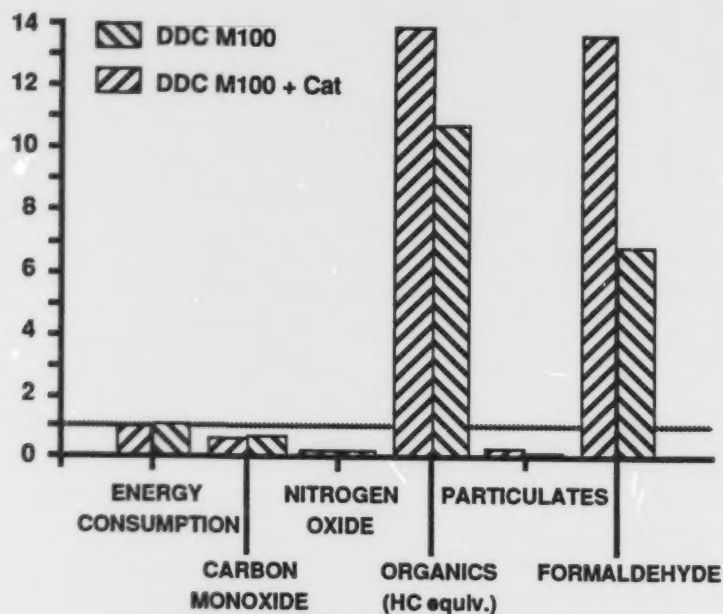


Figure 5/ Performance of Methanol Buses Relative to Baseline Diesel [13]

Because of the large-scale presence of DDC engines in North American transit vehicles, the conversions described in this section represent the most forward development in supplying methanol buses. The most recent data report by DDC represents the performance of engines certified for production in 1991, thus:

Table 8/ Exhaust Emissions Performance of Recent DDC Methanol Engine [14]

Description	Emissions (g/hp-h)				
	HC*	CO	NOx	PM	CH ₂ O
6V-92 TA Methanol	0.4	2.4	2.4	0.05	0.06
1993 EPA Bus Standard	1.3	15.5	5.0	0.1	NA

* Organic matter hydrocarbon equivalent (OMHCE)

Using a catalyst, all emissions are now well within the standard limits, including unburnt methanol. Though operational problems such as limited injector life still exist, recent developments have shown that they will be overcome and consequently this engine will be the prime contender if the methanol option is adopted for Ontario's transit needs. However, other manufacturers have also developed methanol engines and these are described in the following sections.

Cummins L10 Engine

The L10 is a straight 6, 10 L, turbocharged four-stroke commonly found in heavy-duty trucks and is being modified for methanol operation under a program supported jointly by Ontario and Cummins. The conversion strategy in this case is to rely heavily in the first instance on improving the ignition quality of the fuel as this appeared to minimize engine alteration. However, extensive changes are proving to be necessary as the project develops. So far, these include the following:

- Fuel flow rate increase
- Cam profile changes to increase injection rate
- Cam follower changes to optimize injection timing
- New injectors to improve spray pattern
- New pistons for improved combustion chamber shape, and
- Higher compression ratio

It may be that glow plugs will also be necessary to supplement ignition, particularly during start-up.

In development work carried out by ORTECH and sponsored jointly by MTO and Cummins [15], engine operation including starting down to -21 C could be carried out with as little as 0.5% Avocet. However, higher minimum levels are needed to avoid excessive unburnt fuel emissions and rate of combustion pressure rise. This engine will not retrofit into the standard GM buses used in Ontario that presently are fitted with the counter-rotating, transverse mounted DDC engines. However, they can be fitted into other buses such as those manufactured by OBI.

The only field experience with these engines, so far, is in truck service for the City of Vancouver as part of the MILE program where they have accumulated over 30 000 km. The fuel consists of 95% methanol and 5% Avocet. The main problem reported so far has been poor idling and re-starting when hot due to fuel overheating and consequent vapour lock. This may be due to inadequate fuel pressure and circulation at low engine speed. Increased fuel cooling is necessary, which has been accomplished in the field so far by disabling the radiator shutter control. Fuel pumps have been rebuilt and one set of injectors has been replaced. Increased big and small end bearing wear has been observed on the first engine examined. The existing oil is a standard 15W-40 used by the City of Vancouver and a switch to a Cummins selected oil may be made. The Avocet additive seems to eliminate the injector blocking problems encountered in the DDC engines. Volumetric fuel consumption is 2.2 – 2.4 relative to diesel, which is close to equal energy efficiency.

Caterpillar 3306 Engine

The 3306 is an in-line 6-cylinder, 10.5 L, 4-stroke, direct injected engine with turbo-charger and aftercooler which has been modified by the manufacturer to run on straight methanol. Ignition relies on the favourable surface catalyzed ignition property of methanol promoted by a glow plug.

Some of the principal modifications are:

- Use of a glow plug with a special ceramic encasing a metal filament
- Increased fuel flow. The injectors are oil lubricated so no lubricity additive is needed for the fuel.
- Modified injector with an extra hole added axially. This is positioned to spread an ignitable mixture across the combustion space to facilitate the spread of the flame between individual spray jets.
- The injection timing is advanced and of longer duration to accommodate increased fuel flow.

This engine will start at -18°C (0°F) when the glow plug is switched on for 30 s before cranking. In the early configuration, constant power was supplied to the glow plug to maintain an ignition hot spot. Later designs arrange to vary the current: low or zero at high outputs and when fully warmed up while high, when on light loads, or at low temperatures. The main intent is to minimize power consumption, which is supplied from an auxiliary alternator, and to extend the life of the plug whose ceramic surface is slowly eroded by overheating.

Some limited results of engine dynamometer tests have been reported. Steady state results suggest that NO_x is reduced to a half or a third of that for the diesel, dependent on load. At low speeds, apparent hydrocarbons (unburnt fuel) are generally always lower and at high speeds they are also lower except when the load drops off. These emissions consist almost entirely of unburnt methanol and reflect the always present difficulty of compression igniting methanol reliably even with a glow plug when the output is low and the temperature drops.

The engine cannot replace the contra-rotating V6 DDC engines in GM buses without extensive modifications. However, the base 3306 diesel is being used in Eagle type buses operating in at least one U.S. transit property. The methanol engine was evaluated in a heavy-duty, long distance transport operation as part of the MILE program. Total accumulated distance was 330 000 km and 270 000 km on two vehicles at the completion of the test. Wear, based on engine oil analysis, was at least as good as the diesel, and in the case of iron (cyl bores), it was apparently better. The main limiting factor was glow plug durability, which was not more than about 200 hours. Excessive valve seat wear also occurred earlier but this was diminished somewhat by modifications to the seat composition and contact angle. Volumetric fuel consumption was 2.4 times that of the equivalent diesel, which represents a 5% drop in relative energy efficiency.

MAN Spark-Assisted Diesel

The MAN engine is an in-line 6-cylinder, 11.4 L, 4-stroke design which is mounted horizontally. It is noteworthy because the engine is based on a mature concept (stratified charge) originally intended for multi-fuel (broadcut fuel) use. The methanol version is already available in demonstration quantities in MAN designed buses. Principal modifications are:

- The fuel is directly injected into the piston cup.
- A special spark ignition system is used. The plugs have two or, later, three outer electrodes which, with the inner electrode, project far into the cup. A multiple pulsed discharge is applied lasting about 15° which continues beyond the end of fuel injection to ensure complete combustion.

The location of the injector, the shape of the piston bowl, and location and excitation of the plug are critical elements in the design. Though it has had the longest development as a working heavy-duty methanol engine, it is not suitable for installation in Ontario buses without extensive modifications because of its horizontal mounting.

The MAN methanol engine has been extensively evaluated. (Some results are shown in Table 7.) Emissions are extremely low for all components except NO_x; this is mainly due to the use of an oxidation catalyst. As noted under the DDC engines considered earlier, an oxidation catalyst can actually increase NO_x to above the levels in the raw exhaust. The performance of the engine in the manufacturer's buses has also been examined. When compared with the diesel bus, acceleration was slightly less, resulting in about 2 mph less. Fuel consumption over the ADB cycle was almost exactly the same as for the diesel in road tests. Other tests on the engine have also been reported [16]. These indicate a 9% decrease in energy efficiency for the methanol engine over the diesel for a simulated ADB cycle while the torque was about 20% more. Reduction of CO, NO_x, particulates, and hydrocarbons was greater for this engine than for all the others tested in this reference (three diesels, one NG and one propane), attributable, no doubt, to the oxidation catalyst.

Table 9/ Dual Fuel Engine Fuel Consumption and Emissions Performance [9]

Engine/Refuel	Fuel	Fuel Economy	Emissions (g/hp-h)						Comments
		lb/hph	UBF	HC	CO	NO _x	PM	CH ₂ O	
Volvo TD 100A	Meth+Dies	0.476	1.77	1.08	7.12	3.92	0.23	0.064	13 Mode Engine Test
Volvo TD 100A	Pilot Inj	0.489	3.99	1.45	7.67	5.45	0.30	0.187	EPA HD Trans cold+hot
Volvo TD (plus cat)	Meth+Dies	0.473	0.85	0.12	0.62	5.06	0.38	0.104	13 Mode Engine Test
Volvo TD (plus cat)	Meth+Dies	0.486	0.94	0.12	2.69	5.51	0.27	0.194	EPA HD Trans cold+hot
Volvo TD 100C	Diesel	0.432		0.78	2.37	8.86	0.52	0.0012	13 Mode Engine Test
Volvo TD 100C	Diesel	0.474		0.85	3.01	8.34	0.52	0.00q	EPA HD Trans cold+hot

The MAN engine has more than ten years' experience behind it and is the furthest developed application of methanol for heavy-duty engines, including buses. The principal problem, still, is with the special spark plugs needed. The life of present designs is limited and they are replaced frequently as a precaution. Otherwise, failure causes a rich fuel mixture to reach the catalyst causing rapid overheating and destruction. One development being tried to obviate this is to bypass the catalyst when the temperature exceeds a certain value. Plug degradation has proved to be a perennial problem even in conventional spark ignition methanol engines and results from the propensity for surface ignition – the property that is turned to advantage when glow plugs are used. Problems have also been caused by oil leakage into the fuel system via the injector pump. Modification to the lubrication of this pump was under assessment at the last reporting. Used oil analysis has not shown any undue wear, so far, in internal engine surfaces.

An extensive evaluation of driveability and performance of three MAN methanol buses compared with diesel has recently been reported [17]. Driveability was distinctly worse for the methanol buses. This was largely due to poor starting, particularly at low temperatures, and significant hesitation and stumbling. However, acceleration and gradeability were completely comparable. Noise levels for the methanol buses were slightly higher.

Otto Cycle Operation

With its high octane number, methanol is very suitable in principle for Otto cycle, homogeneous charge, spark-ignited combustion. The high latent heat of vaporization and non-miscibility with lubricating oil cause problems in practice. Nevertheless, after extensive development over the last decade, a number of prototype engines built for passenger car application have been made available and are undergoing various phases of demonstration. Heavy-duty engines based on the same principles have not yet advanced so far, most manufacturers attempting to retain the diesel cycle concept as described in the previous section. The following examples represent conversions that have been offered so far.

Daimler-Benz Vaporized Methanol Engine

The Daimler-Benz methanol engine derives from an in-line 6-cylinder, 11.4 L, 4-stroke, horizontally mounted engine which had already been modified for spark ignition for gaseous fuels (propane and natural gas). Adaptation is as follows [18]:

- The methanol fuel is vaporized using the heat from the exhaust and engine coolant and metered through a conventional gas mixer.
- Start-up is accomplished with an auxiliary combustion heater which vaporizes the fuel until the engine is warmed up.

The benefits of using vaporized fuel are increased efficiency due to exhaust heat recovery and the elimination of cylinder washdown and oil contamination. This avoids a major cause of reduced engine durability. The uniformity of distribution in the manifold enables

the full lean flammability range of methanol to be used up to an air/fuel equivalence ratio equal to 1.8 so that operation can be unthrottled over the high output end of the range, further enhancing efficiency. The flat engine could not be put into a GM bus without extensive modifications but it has been demonstrated in Daimler-Benz buses.

The output power of the methanol gas engine is equal to the diesel from which it is derived. Though the volumetric efficiency is reduced by the induction of vapour which displaces some air – and by the flow resistance of the gas mixer, the losses are made up for by operation closer to stoichiometry because there is no smoke limit. At lower engine speeds the methanol engine even offers higher torque than the diesel – a characteristic of spark ignition. The energy efficiency of the latest engine reported was substantially the same as the diesel at the optimized compression ratio (12.5:1) and with load-controlled timing.

Field experience has been reported from demonstrations in New Zealand, West Germany, and South Africa [11]. For a total accumulated distance of 245 000 km, the average fuel economy ranged from 4.84 to 6.28 mpg with the comparable diesel figure at 6.28. Analyses of used engine oil for trace wear metals show no undue engine wear. The oil does show increased absorption of acidic products from methanol combustion (formic acid). A conventional oil has been used with no extra additives for increased basicity (high total base number, TBN) that have been found necessary for smaller liquid methanol burning spark ignition engines. Results are awaited of detailed engine examination after teardown at about 200 000 km per vehicle.

The starting procedure has been improved by thermostatic control of the heat exchanger coolant circuit and by insulation. This has enabled restarts to be made 40 – 80 minutes after shut down without further application of the auxiliary burner.

Dual Fuel Operation

A number of dual fuel (methanol and diesel) applications have been developed that could be suitable for heavy-duty vehicles. Unlike operation on straight methanol, it cannot be certain that such engines will meet all the strict new standards for emissions – particularly smoke. It is conceivable that such combination use may be good enough to clean up in-use engines to a degree that will satisfy local air quality requirements. Retrofitting involves additional complications because of the need for an extra fuel tank, fuel pump, and a proportioning system. A doubling of fuel storage at garages would also be needed. Discussion will be confined to systems that have already been developed as prototypes by manufacturers and installed on buses for demonstration.

K-H-D (Deutz) System

The base Deutz design is a V8, direct injected, air cooled diesel. Diesel pilot injection is used for methanol ignition. Principal modifications are as follows [19]:

- An additional methanol fuel tank and supply pump is installed.
- An auxiliary injector is installed for the methanol fed by a distributor-type injection pump.

- Fuel flows are controlled separately so that the diesel fuel is used alone for start-up and light loads while methanol is added for heavier loads.

In a demonstration in West Germany, a bus with a methanol/diesel Deutz engine had accumulated 180 000 km at the time reported. The percentage of diesel fuel needed dropped to a range between 22% and 46%, with an average of 31%. It was estimated that the particulates could be lowered by up to 90% by using methanol in this way. Internal wear has appeared comparable with diesel engines. Auxiliary components have, however, experienced increased degradation. The submerged fuel pump had an average life of about 20 000 km due to commutator erosion. Injection nozzles also have reduced life expectancy with the needle seats receding sufficiently by 50 000 km to lower injection pressure by about 15%.

Volvo Dual Fuel System

The base Volvo diesel is a 9.6 L, 6-cylinder, turbocharged direct injected design. Diesel fuel pilot ignition is used with other modifications, thus:

- A small distribution pump and single-holed injector is used for the pilot diesel, sized sufficiently for the moderate fuelling rate required. The original injector and supply system is used with the methanol.
- Cold start-up employs an air pre-heating system; diesel fuel is used alone.

The engine has been tested with and without an oxidation catalyst and its results compared with the base diesel engine, shown in Table 9 [9]. Without a catalyst, unburnt fuel and CO are greater than for the diesel while particulates and NOx are reduced. The catalyst greatly reduces all emissions except NOx which is increased (though still only about 60% of the diesel engine value). Fuel consumption in energy units is about 10% more for the methanol engine. Over the transient cycle, about 80% of the fuel mass used was methanol while over the 13-mode cycle the methanol used was about 50%.

3.2.6/ Equipment Cost

The only viable supplier for methanol bus engines in the immediate future is DDC whose methanol converted 6V-92TA engine was discussed above. As supplied in demonstration quantities, so far a substantial premium has been charged to enable the company to recover its developmental costs. A demonstration now being arranged at Windsor Transit involving six methanol buses includes a cost premium of \$45,000 for the conversion over the standard bus cost. This includes not only the engine itself but the modifications to the bus including stainless steel tanks and lines, special fuel pumps, filters and coolers, and flammable vapour detection equipment. In a mature configuration and factored over a larger production volume, these costs would be reduced.

Tables 10 and 11 indicate the estimated costs of methanol engines and buses respectively for present day and mature configuration and compared with the baseline diesel. The year 2000 engine could be either diesel cycle (compression ignition) or Otto cycle

(spark ignition) but the costs of the electronic governor/fuel management system is supposed to be the same (\$2500). The zero provincial sales tax for the near-term methanol bus applies at present to all alternative fuelled buses. It was assumed that this tax would be restored by the year 2000, as the technology matures.

Table 10/ Methanol and Diesel Engine Cost

Description	Diesel	1989 Methanol	2000 Methanol
Base Diesel Engine	\$12,500	\$12,500	\$12,500
Injection/Governor System	\$ 2,500		
Methanol Fuel System		\$ 500	\$ 500
Governor (Electronic)		\$ 3,000	\$ 1,500
Ignition System		\$ 1,000	\$ 1,000
Catalytic Converter		\$ 3,000	\$ 2,500
Per Engine Development Cost		\$10,000	
Net Engine Cost	\$15,000	\$30,000	\$18,000

Table 11/ Bus Capital Cost

Description	1989 Diesel	1989 Methanol	2000 Methanol
Bus Without Engine	\$156,815	\$156,815	\$156,815
Engine	\$ 15,000	\$ 30,000	\$ 18,000
Fuel Tank/Line		\$ 3,000	\$ 3,000
Development		\$ 10,000	\$ 0
Bus Subtotal	\$171,815	\$199,815	\$177,815
P.S. Tax (8%)	\$ 13,745	\$ 0	\$ 14,225
TOTAL	\$185,560	\$199,815	\$192,040

3.2.7/ Summary of DDC Engine Demonstrations

Test details have been given in the previous sections under the heading, Available Technology. Only DDC engines are considered front runners for the North American market. Starting from only a few buses, the number has increased rapidly of late so that by the end of 1989 the total number of methanol engines tested had reached 80 with an accumulated bus mileage of more than 900 000. The following is a summary of DDC methanol bus demonstration activities in North America:

- Golden Gate Transit District: this was started in 1984 with two buses.
- Medicine Hat, Alberta: two in use with order for three more.
- Winnipeg Transit: two buses.
- Denver, Colorado: thirty-five vehicles were in operation by May, 1989.
- Southern California Rapid Transit District (SCRTD): thirty vehicles in operation by late 1989.
- Triboro, New York: five buses

3.3/ Natural Gas for Vehicles

3.3.1/ Fuel Characteristics

Natural Gas for Vehicles (NGV) primarily consists of methane (CH₄) and to a smaller extent other hydrocarbons such as ethane, propane, butane, pentane along with impurities such as nitrogen, carbon dioxide, water, and sulphur compounds. Gas suppliers are required to sell "pipeline quality" gas (Table 12) which typically contains 1.0 mg/m³ of hydrogen sulphide (H₂S) and 50.0 mg/m³ of water vapour. The specific gravity with respect to air is nominally 0.58 and the energy content (lower heating value) is 47.4 MJ/kg. In Ontario, the methane content of natural gas usually exceeds 95% by volume.

Table 12/ Typical Composition of Canadian Pipeline Quality Natural Gas [20]

Natural Gas Component	% By Volume
Methane	95.4%
Ethane	2.0%
Nitrogen	1.9%
Carbon Dioxide	0.4%
Propane	0.2%

Methane has a boiling point of -162°C. Under all normal ambient temperature conditions, it is a gas with very low density (Table 12). Therefore, it must be compressed to 20.7 MPa (3000 psig) to provide sufficient energy for reasonable vehicle range. Because of the high pressures required, the fuel is stored in high strength cylinders. Fuel lines, valves, and related equipment are designed to withstand this working pressure.

NGV's energy content on a mass basis exceeds that of diesel fuel by about 14% (47.4 MJ/kg vs. 42.9 MJ/kg for diesel). Diesel, being in liquid form, has a density of about 0.84 kg/L. NGV density (gaseous) is only 0.70 kg/m³ or 0.00070 kg/L at atmospheric pressure. Even at 20.7 MPa (3000 psig) and 21.1°C (70°F), NGV density is only 0.175 kg/L or 22% of diesel density. The net effect of these two factors is that NGV requires approximately four times the storage volume of diesel to contain an equivalent amount of fuel energy.

3.3.2/ Fuel Supply

Canada exports about one-third of its natural gas production to the U.S. Currently, NGV accounts for only 0.07% of Canada's retail transportation fuel usage [21]. Canadian natural gas reserves will be sufficient to meet Ontario's urban transportation energy needs far into the future. Similarly, fuel quality is not expected to be a problem. The only major issue, in a few localities, is the control of water content during winter months to prevent hydrate formation in fuel system passages and corrosion of steel storage tanks.

There are currently (as of mid-1990) 40 retail natural gas filling stations in Ontario. Most natural gas suppliers are willing to provide dedicated compression/refuelling facilities to large fleets and charge a compression cost in addition to the fuel cost to provide a reasonable return on their investment. The compressor electrical bill is an additional expense for the user. Such is the case at HSR (Hamilton Street Railway).

3.3.3/ Industry Pricing Strategies

The NGV price in Ontario is affected by a number of factors. The first is the Alberta well head natural gas price of \$1.50/GJ (5.67 ¢/m³ - May 1990). The recent historical trend of Alberta and Ontario industrial natural gas prices is presented in Table 13. Another major influence is the cost of compressing the gas which is strongly influenced by compressor utilization and suction pressure.

Table 13/ Representative Industrial Natural Gas Prices [22]

Natural Gas Prices (¢/m ³)		
Year	Alberta	Ontario
1978	3.60	7.20
1979	3.60	7.80
1980	4.94	8.95
1981	6.99	11.42
1982	7.15	15.80
1983	7.87	15.80
1984	7.55	15.80
1985	7.77	15.70
1986	7.73	15.26
1987	7.81	13.42
1988	6.78	13.24
1989	5.23	12.82

The compression capacity will depend on the type of fill process desired, fast-fill or slow-fill. The fast-fill option allows vehicles to be refuelled individually in a matter of minutes. A fast-fill facility requires large compressor units and associated buffer storage, which can be more expensive than the slow-fill option. Slow-fill systems usually employ multiple refuelling lines allowing simultaneous refuelling of many vehicles over a period of hours. The choice of fast-fill versus slow-fill depends on the amount of time and space available for refuelling to take place. For both cases, the cost of electricity and maintenance must also be considered.

Two typical options for purchasing the refuelling facility are described below. It is possible to purchase the refuelling station outright, or lease the facility (reducing capital needs) from the local gas company. When a gas utility leases the compressor station, an incremental amount is added to the fuel price to reflect the life-cycle cost of the facility and provide an adequate return on the company's investment.

In the present (mid-1990) market the ownership option for a fully-utilized facility may result in a compressed natural gas cost of about \$0.32/kg (\$0.22/m³) to large fleet customers. This includes a basic gas cost of \$0.12/m³ plus \$0.015 for compressor maintenance, \$0.015/m³ for electricity and \$0.07/m³ for the amortization of the facility. At present, no provincial or federal sales and excise taxes are applied to NGV.

3.3.4/ Natural Gas Engine Technology

Natural gas engines for transit buses are not yet available in production quantities. The engines that have been developed to date are prototypes for evaluation purposes. However, some of the major engine manufacturers are presently getting ready to commence the supply of production engines in 1991.

Monofuel, NGV Spark Ignition Engines

One approach to using natural gas in heavy-duty engines is to employ spark ignition. Natural gas will not compression ignite easily, so an ignition source is required. Such an engine is usually throttled in the intake tract and uses a standard automotive ignition system.

For heavy-duty use, a modified diesel block offers the promise of long life. Since a diesel does not employ an ignition system, major engine modifications are necessary. These include modifying injector mounting points to accommodate spark plugs and possibly spark plug well tubes, the addition of a distributor drive or crankshaft position sensor, an engine speed governor, a throttle body, and new lower compression ratio pistons. The use of throttling and a lower compression ratio result in a small efficiency loss.

Ontario's experience with this technology began with the IVECO 8220R CNG engine, which was developed in 1984-85 by DERECO in Switzerland. It is a 9.6 L, 170 HP six-cylinder naturally aspirated unit operating in reverse rotation. It is designed to be fitted to a GM V-drive bus with suitable engine cradle modifications. This is the engine presently in use at HSR in Hamilton.

Ontario has also participated in the development and testing of the Cummins L10 NGV engine at ORTECH International. This is a 10 L, 220 to 280 HP turbocharged six-cylinder engine. The carbureted version of this engine has been installed in three 96" wide and one 102" wide, 40-foot long OBI Orion buses for evaluation in the cities of Mississauga and Toronto.

The job of converting an existing diesel engine to spark-ignited natural gas use involves the following items. First the engine compression ratio must be lowered from about 17:1 to approximately 12:1 for naturally aspirated engines and about 10:1 for turbocharged engines. This is accomplished by installing revised pistons. To help reduce emissions of unburned fuel, a low valve overlap (less than 20 crankshaft degrees) camshaft is usually selected.

A throttle body is also required since engine power output is now controlled by air/fuel mixture quantity rather than quality. Since the presence of an intake throttle results in a vacuum condition in the intake manifold, intake valve stem seals are added to reduce oil consumption. The cylinder head must be revised to accept spark plugs. Normally, the injector holder holes are enlarged and threaded. In some cases this revision breaks into the water jacket and valve train areas so spark plug tubes are added and sealed to prevent coolant and engine oil leakage. These must be designed to stay locked in place when the spark plugs are installed and removed during normal servicing (see Figure 6).

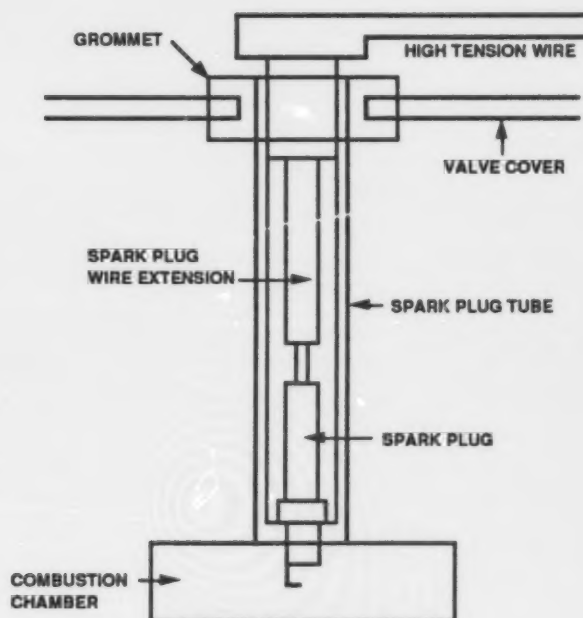


Figure 6/ Typical Spark Plug Tube Installation

A provision for driving a distributor or, alternatively, a crankshaft position sensor, is added to allow for proper spark timing. A high tension coil set and wires are installed to feed power to the spark plugs. The latest ignition systems are employing the distributorless concept with ignition coils for each cylinder or each pair of cylinders. Future systems may use small coils mounted directly on the spark plugs eliminating the need for high tension wires (the so-called 'Direct-Fire' ignition systems). An electronic ignition controller is then programmed or the distributor weights and springs are calibrated with the desired spark timing characteristics.

Finally an NGV fuel system is added and calibrated. Since diesel engines run lean by design, engine power output can actually be increased when using NGV by employing a stoichiometric air/fuel mixture (no smoke limit). This results in substantially higher valve and exhaust gas temperatures and higher exhaust emission and fuel consumption. Therefore, the turbocharged lean-burn approach appears to be the best strategy. Thus,

exhaust valve temperatures can be kept in the normal range (the same as that of the diesel version of the engine).

Some concerns arise when extremely lean mixtures are used. The mixture burn rate slows as the mixture becomes leaner. If combustion is not completed by the time the intake valve opens, the air/fuel mixture in the intake manifold can be ignited. Since the consequence is a damaged intake manifold, pressure relief pop valves are used to prevent an induction backfire from causing permanent manifold damage. Also possible is an exhaust system backfire due to engine misfire when operating extremely lean. This causes a substantial amount of unburned fuel to enter the exhaust system where it can ignite, possibly damaging the exhaust system. This can also happen after an extended, closed throttle deceleration followed by a rapid acceleration. The fuel control system must be configured to eliminate these conditions. Precise air-fuel ratio control is also required to ensure the lowest possible exhaust emission levels.

For automotive applications such as buses, an engine speed governor system is added to prevent engine overspeed as well as provide idle speed control. This can be either a mechanical or electronic system controlling throttle position independently of the driver demand. Less desirable are systems that cut off fuel flow or ignition spark since they can also cause exhaust system backfire and overheating of catalysts.

Table 14 illustrates the expected long-term production cost of a monofuel NGV bus engine where the economies of scale allow a direct add/delete list approach.

Table 14 - Net NGV Engine Cost (Long-Term)

Description	1989 Diesel	1989 NGV	2000 NGV
Base Diesel Engine	\$12,500	\$12,500	\$12,500
Injection/Governor System	\$ 2,500		
Governor			
NGV Fuel System		\$ 500	\$ 500
Governor (Electronic)		\$ 3,000	\$ 1,500
Ignition System		\$ 1,000	\$ 1,000
Catalytic Converter		\$ 3,000	\$ 2,500
Per Engine Development Cost		\$10,000	
Net Engine Cost	\$15,000	\$30,000	\$18,000

Dual Fuel - Diesel Pilot Ignition NGV Engines

The auto-ignition temperature of natural gas is about 650°C as compared to approximately 250°C for diesel fuel. Thus it is difficult to compression ignite natural gas. A source of ignition is therefore necessary. In a dual-fuel arrangement, the basic diesel combustion process is preserved in that a small injection of diesel fuel called a pilot injection is ignited by compression heating. This pilot flame then ignites the air/natural gas mixture.

The natural gas is supplied by a standard NGV fuel system and mixer unit. The quantity of natural gas admitted to the engine is directly related to the diesel pilot injection control. The engine does not require throttling on the air intake side and so engine volumetric efficiency is better than that of the spark ignition engine under some part-load conditions, especially idling when the engine operates on 100% diesel fuel (no natural gas is used).

Engine power output is primarily controlled by varying the amount of natural gas admitted to the engine. The main requirement of the fuel system is the matching of the diesel fuel flow and injection timing to the natural gas flow as engine speed and load changes. At low engine loads, diesel fuel is used since the lean air/fuel ratios used are below the lower ignition limit for natural gas in air. As engine load increases, natural gas is added but will not ignite until the lower ignition limit is reached. Once the mixture is above the lower limit, the engine output can be increased by adding more and more natural gas. The diesel fuel flow can be reduced accordingly until, at full load, up to 90% substitution of diesel is achieved (for short periods of time).

While the dual fuel arrangement reduces the amount of modification work required for the engine, two fuel supplies must be maintained. Mercedes-Benz has reported unacceptably high diesel injector tip temperatures at even the 70% diesel substitution level [23]. The mechanical systems used to control fuel flow rates are at best a compromise so the need for precise electronic control is indicated. Low engine load combustion is slower, exhaust temperatures increase, and fuel efficiency is reduced (except at idle) compared to the standard diesel. These engines also suffer from very high rates of pressure rise within the cylinder at peak engine loads which can adversely affect engine life if not carefully controlled.

A considerable amount of dual fuel research has been performed in Canada at the University of Calgary [24], BC Research, and the University of Victoria [25]. BC Research has concentrated its efforts on modern diesel engine conversion to dual fuel operation. In a recent program, a Cummins L10 engine was modified to allow operation on any combination of diesel fuel and natural gas [26]. Engine emissions and performance were recorded for a variety of steady-state speed, load, and fuel mixtures. HC and CO emissions were higher than the baseline diesel but NOx was reduced. Thermal efficiency was comparable at peak loads but at part loads was 30% lower than the baseline diesel engine. Attempts were made at the University of Calgary to evaluate the effects of intake air preheating and throttling on a Ricardo Hydra indirect injection configuration engine but only slight efficiency gains were noted [7]. The final recommendations included studying exhaust gas recirculation, stratified charge engines, and variable pilot injection timing.

Caterpillar has developed a prototype four-stroke dual fuel engine in co-operation with BC Research, using a computerized fuel system controller, but no data have yet been published on its performance and emission characteristics. The latest phase of this program will assess the wear characteristics of dual fuel operation versus the standard diesel engine.

Pro Staff Fuels of Vancouver has developed a retrofit kit for the existing two-stroke DDC 6V71 bus engine and has installed its device on two Tacoma, Washington buses. Experience to date has been mixed with some piston failures early on in the test period (probably due to excessive rates of pressure rise). Further refinements to the system may improve the durability and performance but meeting emission standards and keeping diesel injector tip temperatures within acceptable limits with the dual fuel concept will be challenging.

The more sophisticated systems for two-stroke engines (such as the Stewart & Stevenson Power/ORTECH program) utilize high speed electronic injectors to accurately time the injection to each cylinder inlet port (Figure 7). This reduces the amount of fuel lost during the scavenging period when the exhaust gases are leaving the cylinder.

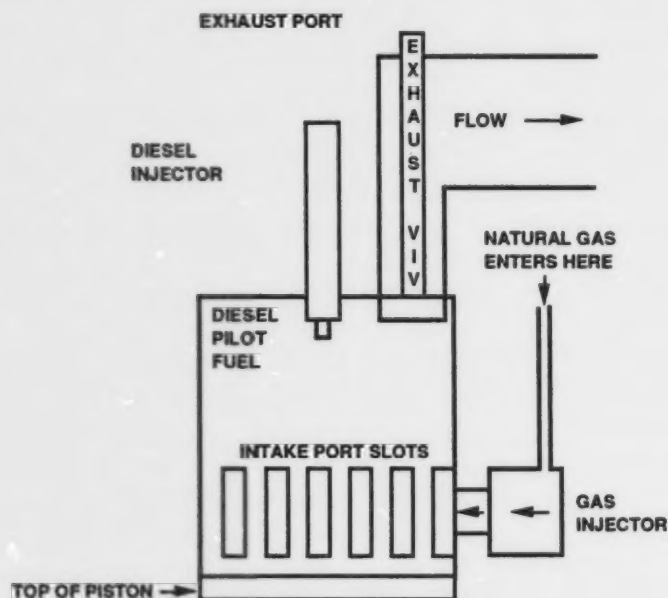


Figure 7/ Dual Fuel NGV/Diesel Engine (2-Stroke)

The use of diesel fuel for mixture ignition still results in the formation of reactive particulate matter albeit at lower levels than a standard diesel. One added benefit is the ability to run on 100% diesel fuel should the natural gas supply run out or be unavailable. Table 15 is a qualitative comparison of the dual fuel and the mono-fuel approaches.

Considerable development work continues to be done to produce reliable, clean dual fuel engines.

Table 15 - Comparison of Mono-fuel versus Dual Fuel NGV Engines

Item	Mono-fuel	Dual Fuel
Exhaust Emissions	Lower	Higher
Rate of Pressure Rise	Lower	Higher
Engine Modifications	Major	Minor
Cycle Efficiency	Lower	Higher

On-Board Fuel Storage

NGV is stored in high-strength cylinders made of steel, aluminum, or either of these combined with fibre/resin reinforcement. Since they are high-strength, they are very resistant to penetration during vehicle impact. They are bulky, however, and add a substantial amount to the weight of the vehicle. Each cylinder is equipped with one or more temperature sensitive pressure relief devices (PRDs) to vent the tank in a controlled manner when it is exposed to high heat or fire. The main problem in bus applications is finding room under the floor of the bus for the tanks. Therefore, roof-mounting of cylinders has been adopted in the Ontario program. Roof-mounting also keeps the cylinders and fuel lines away from potential collision areas. Also, since natural gas is lighter than air, any gas released will rise up and away from the vehicle occupants.

Advances in fuel tank design are meant to reduce weight while maintaining or improving corrosion resistance, strength, and cylinder life. The traditional steel cylinders are being supplanted by aluminum, fibre wound aluminum, and fibre wound steel types. The fibre wound or composite cylinders take advantage of the high directional strength per unit weight of such advanced fibres as Kevlar, E-glass, and R-Glass. Relatively thin cylinder walls of metal are reinforced by the fibres and encased in resin. In some cases this is a one-step procedure whereby a pre-impregnated fibre tape is heated just prior to winding on the cylinder (under tension, in the case of autofrettage), where it bonds to the other tape layers on cooling. This pre-stresses the aluminum liner in compression in the hoop direction which results in lower liner tensile hoop stresses when filled to operating pressure. The volume of NGV stored per unit cylinder weight is an important on-board storage issue. This characteristic is quantified by a performance factor, which is provided in Table 16 for cylinder technologies of the day.

Alusuisse is one of the composite cylinder manufacturers capable of supplying 0.33 m diameter cylinders in any desired length from 1.8 to 6.1 m (6 to 20 feet) and with a working pressure up to 24.8 MPa (3600 psig). Some characteristics of these cylinders are summarized in Table 17.

A typical urban bus has a 545 L (120 imperial gallon) diesel tank which when full weighs approximately 500 kg. As an example, the use of 0.33 m diameter by 6.1 m cylinders means about 350 kg per full cylinder plus the weight of any additional support structure. The use of four such cylinders implies a 1000 kg weight penalty over diesel. This 1000 kg weight penalty (equivalent to thirteen 75 kg passengers) applied to a 16 000 kg GVW

Table 16/ Comparison of NGV Storage Cylinder Technologies

Cylinder Technology	Performance Factor*
All Composite	0.411-----0.530
Steel All Wrapped	0.223-----0.338
Aluminum All Wrapped	0.303-----0.433
Steel Side Wrapped	0.219-----0.291
Aluminum Side Wrapped	0.276-----0.377
Steel	0.129-----0.142
Aluminum	0.190-----0.200
Aluminum Steel Overwrap	0.190-----0.232

* Performance Factor = Volume of NGV stored in
m³/cylinder weight in kg

Table 17/ Alusuisse Aluminum/Fibre Wound NGV Cylinders

Length (m)	Water Cap. (L)	NGV Storage (kg)	Empty Weight (kg)
1.8	118	19.5	88
2.1	139	22.9	103
2.4	160	26.4	118
3.0	203	33.5	147
3.7	245	40.4	178
4.6	338	55.8	241
6.1	407	67.2	289

Storage pressure is 20.7 MPa (3000 psig) at 21° C
All above cylinders are 0.33 m (13") O.D.
Compressibility Z=0.82

bus would result in a moderate fuel consumption increase. The diesel/NGV volumetric fuel consumption experienced in actual revenue service has shown a 10-15% higher fuel consumption for the L10-equipped natural gas buses over the standard DDC 6V92.

With four Alusuisse 6.1 m by 0.33 m diameter NGV aluminum, fibre-wrapped cylinders at 3000 psig, the resulting diesel equivalent storage capacity is 340 L (75 imp. gal.), which provides a vehicle range of 560 to 800 km (350 to 500 miles) depending on route conditions. Fleet experience to date indicates an average diesel equivalent fuel economy value of 63.1 L/100 km (4.5 mpg), so an effective range of 544 km (340 miles) has been demonstrated. If one wishes to use under-body cylinders of 2.1 m (7 foot) length, for equal NGV storage, twelve are required. Each full cylinder weighs 125 kg so the weight penalty is about equal to the four 6.1 m cylinder case.

Fuel Lines

High strength stainless steel fuel lines are used to handle all high pressure gas requirements. These lines are corrosion resistant and very strong. High quality fittings must be

used to ensure adequate durability without leakage. Once the pressure is reduced by the first stage pressure regulator, the same flexible lines as used with propane fuel may be employed (nylon hose with braided stainless steel shield and plastic jacket Type 3). The dry hose from second stage regulator to mixer is made of a rubber impregnated fabric. For the case of the single unit three-stage regulator, only the stainless steel high pressure lines are used with a low pressure dry hose feeding the carburetor.

To handle the high fuel flow rates expected in transit bus refuelling operations, a 0.75" diameter stainless steel manifold will be required. Smaller 0.5" diameter lines will feed gas to each cylinder from this main manifold. It may also be necessary to obtain tank valves with larger internal orifices to support flow rates approaching 1250 SCFM per cylinder (5000 SCFM total).

Bus Engine Development Programs

Since the early 1980s MTO has been working with ORTECH to develop properly engineered heavy-duty automotive gaseous fuel engines. In 1985 MTO, ORTECH, and Cummins Engine Company started to develop an NGV version of the Cummins L10 diesel engine. This diesel engine is currently offered by some bus manufacturers as an option. As of June 1990, several carbureted prototype versions have been built, their fuel consumption and emission characteristics have been mapped, and they have been installed in four buses. The exhaust emission levels for the production natural gas engine are expected to be 1.0 (HC), 4.5 (NOx), 0.3 (CO), and 0.06 (PM) g/bhp·h.

The major NGV technology program now (1990) under way at ORTECH is the development of an advanced, computer-controlled fuel delivery system called GFI (Gaseous Fuel Injection) for the Cummins L10 turbocharged NGV engine. The intent is to develop an extremely lean burn NGV engine of adequate power and torque, yet low exhaust emissions. Testing to date (June 1990) has been promising. The program goal is to develop an NGV engine that meets the proposed 1991 U.S. EPA urban bus diesel engine exhaust emission standards. At present (June 1990), no emission standards apply to natural gas engines. However, it is anticipated that standards comparable to those for diesel engines will be proposed by EPA.

The main uncertainty in this regulatory process is whether or not methane emissions, which are non-reactive, will be included in the total hydrocarbon standard. If they are included, most NGV engines will require a catalytic converter. Conversely, if they are not included, the need for the catalytic converters may diminish. However, given the widespread concern with the greenhouse effect, the use of catalytic converters still may be desirable and therefore Ontario natural gas buses will be so equipped.

The first experience with heavy-duty natural gas engines in Ontario has been with the IVECO 8220R four-stroke, spark-ignition engine as converted by DERECHO of Switzerland. Seven buses are in operation at Hamilton Street Railway using this engine. In a bus engine evaluation program at ORTECH, the IVECO natural gas engine was tested for emissions, fuel consumption, and performance versus DDC 6V71 diesel, IVECO LPG, IVECO diesel, MAN diesel, and MAN methanol engines in 1986 [27].

Due to less than expected energy efficiency results, a small optimization program was initiated to try to improve fuel efficiency and reduce nitrogen oxide emissions. The engine was mapped for fuel consumption and emissions across its speed and load range with the intent to operate the engine as lean as practicable. Unfortunately, the engine did not produce adequate power for transit bus applications at lean mixtures. An attempt was made to maintain the required engine power when needed by enriching the fuel mixture and retarding the ignition timing with increasing engine load but only a small reduction (approximately 14%) in oxides of nitrogen emissions was achieved. This approach (at least for this engine) was therefore abandoned.

A GM 454 V8 NGV engine is currently installed in a 30-foot OBI (Orion) bus in Mississauga. This vehicle has been operational since June 1987 and represents a different approach to transit bus NGV use. The GM medium-duty engine was converted to NGV with the intent of trying a less expensive but less durable engine in daily transit service. The result of this program will be the assessment of the "throw away" engine concept in which it is expected to be cheaper to replace than to rebuild the engine once it is worn out.

Alternative Exhaust Emissions Control Strategies

If the turbocharged lean burn approach, which was discussed above, were not to meet the 1991 requirement, a stoichiometric approach with three-way catalyst system would have to be employed. This concept has the unfortunate drawback of increasing exhaust gas temperatures beyond that of a typical diesel engine. The result would be reduced valve and valve seat life unless special high temperature capable materials were employed (at increased cost). Such engines can use existing exhaust gas oxygen sensors in a feedback control loop to maintain precise air-fuel ratio control. The three-way catalyst would oxidize CO and HC while also reducing NO_x allowing the engine to meet the 1991 standards but at increased cost similar to or higher than that of the diesel particulate trap system.

Hardware Compatibility

To date, no insurmountable hardware compatibility issues have surfaced. NGV, being a clean, dry gas, has the potential for causing accelerated valve seat wear but this problem can be overcome with proper valve and valve seat materials, and by limiting exhaust gas temperatures.

Engine lubricants specific to gas engines are available, but they have been designed for use in stationary engines. These tend to be low ash oils with reduced amounts of anti-wear additives. Thus, some lubricant development work may be necessary to ensure that sufficient anti-wear components are present while oil thickening and combustion chamber deposits are minimized.

3.3.5/ NGV Transit Bus Demonstrations

Ontario Experience

Ontario experience with natural gas in transit buses began at Hamilton Street Railway (HSR) in 1985. Six GM 40-foot buses have been converted to operate on natural gas using the IVECO 8220R NGV engine. Total fleet distance accumulation to date (June 1990) has been 650 000 km. During this period fuel energy consumption has been about 28% higher than that of the DDC 6V71 NA engine in the same type of bus. Recent installation of better mixer units and consolidation of NGV bus operations to a single garage have helped stabilize seasonal variations in fuel consumption. HSR is now reporting fuel consumption values virtually identical to those experienced at TTC and Mississauga Transit with NGV L10 buses (about 4.0 miles per imperial gallon diesel equivalent). (see Table 18)

Table 18 - NGV Bus Fuel Consumption Comparison

Transit Operator Location [Engine - (Fuel)]	Average Diesel Consumption [MPG]	Average NGV Consumption [MPG] (Diesel Equiv.)
Hamilton (HSR) 6V71 (Diesel) - IVECO 8220R (NGV)	4.9	4.0
Mississauga (MT) 6V53 (Diesel) - GM 454 (NGV)* L10 (Diesel) - L10 (NGV) 6V92TA (Diesel) - L10 (NGV)	6.6 6.5 5.1	6.2 4.4 4.4
Toronto (TTC) 6V71 (Diesel) - L10 (NGV)	5.4	4.3

* - 30 foot OBI Bus (All others are 40 foot GM, Flyer and OBI buses)

HSR is presently expanding its NGV bus fleet to ten buses by retrofitting existing buses. As of June 1990, seven buses are in daily revenue service.

Additional experience has been gained at Mississauga Transit where a 30-foot OBI bus was converted to natural gas using four six-foot-long by thirteen-inch diameter cylinders giving a total storage capacity of 4300 SCF. The engine is a GM 454 CID V8 gasoline engine converted to natural gas. Experience to date has indicated a fuel energy consumption rate about 10% higher than the standard DDC 6V53 diesel engine in the same type of bus. The total distance accumulation on this bus has been about 40 000 km through June 1990.

Mississauga Transit also operates a 96" L10 NGV bus equipped with an automatic data logging system which provides continuous statistical data on critical system pressures, temperatures, speeds, and fuel mass flow rate.

The Toronto Transit Commission (TTC) has approved a plan to purchase 25 NGV buses for evaluation purposes. After a suitable test period, a decision will be made regarding fleet expansion up to 125 units.



Figure 8/ First TTC Natural Gas Bus

Two 96" prototype OBI NGV L10 buses have been delivered to TTC for initial evaluations in revenue service. The first TTC 102" OBI NGV L10 bus is to be delivered in June 1990. One 96" and the 102" bus have also been equipped with data collection systems.

As of mid-May 1990, the three 96" NGV L10 buses have averaged 4.4 miles per imperial gallon diesel equivalent while three 4-stroke (L10) diesel control buses averaged 6.5 mpg. The three two-stroke (1977 6V71) buses averaged 5.0 mpg. The energy consumption penalty observed is thus 32% with respect to the four-stroke L10 and 12% with respect to the two-stroke 6V71. All of the above buses are operating on similar high-density routes to ensure a valid comparison.

World Experience

In the United States, Washington Natural Gas has worked with Pierce Transit to convert two two-stroke diesel buses to NGV using the Pro Staff Fuels dual fuel conversion kit. Southwest Gas Corporation and the city of Phoenix have converted one four-stroke

MAN bus to dual fuel operation with a 20% NGV substitution rate. The goal is to reduce visible smoke emissions.

The Los Angeles County Transportation Commission intends to purchase ten dedicated NGV buses and will convert two diesel buses to dual fuel operation. Brooklyn Union Gas Company has taken delivery of two OBI Orion 40-foot buses equipped with GM 454 V8 turbocharged NGV engines. A stoichiometric fuel control system with three-way catalyst has been fitted to each bus prior to revenue service for emission control purposes. Testing of this engine configuration at EPA yielded excellent emission results well below the 1991 urban bus requirements.

In early 1989, one of the Brooklyn buses was hit by a car broadside as it left the NGV refuelling station. The impact displaced several of the under-body fuel cylinders and resulted in substantial fuel leakage. Eventually, the tank valves were shut off by firefighters although no fire occurred. This incident points out the need for adequate side impact protection and/or locating the fuel tanks on the vehicle roof.

In Perth, Australia, there are approximately 40 dual fuel buses using Mercedes engines. Brazil also has a major bus conversion program employing Mercedes engines. Bangkok, Thailand, has one MAN NGV bus. There are buses in Italy running a dual fuel system with up to 80% diesel substitution by NGV. New Zealand, China, and the USSR all have natural gas bus programs. In each case, the emphasis has been on demonstrating an operational capability rather than meeting any specified exhaust emission standards. The Ontario program has the goal of meeting the U.S. EPA 1991 heavy-duty diesel emission standards for urban buses while ensuring vehicle safety, reliability, and efficiency.

3.3.6/ Environmental Impacts

NGV mono-fuel, spark-ignited engines, as with most internal combustion engines, produce hydrocarbons, carbon monoxide, carbon dioxide, nitrogen oxides, and water vapour in their exhaust. Natural gas exhaust hydrocarbon emissions are typically 70-80% methane which is considered a benign, natural component of the atmosphere. It does, however, act as a powerful greenhouse gas and thus every effort is being made to reduce methane emissions via an oxidation catalyst. Multiple component fuels such as diesel emit more reactive hydrocarbons, some of which are carcinogenic. A lean-burn NGV engine with oxidation catalyst will emit low levels of hydrocarbons, carbon monoxide, and nitrogen oxides. Stoichiometrically fuelled NGV engines tend to have high nitrogen oxide levels compared to diesel engines; tend to have very high part-load hydrocarbon emissions and correspondingly low thermal efficiency, except at peak engine loads.

3.4/ Propane

3.4.1/ Characteristics and Availability

Fuel grade propane, designated "HD5" in North America is composed of a minimum 90% propane and up to 10% other chemicals such as butane, carbon dioxide, and propylene (Table 19). In Ontario, HD5 is typically at least 95% propane.

It is also required that propane be odorized by the addition of 1.0 kg ethyl mercaptan, 1.0 kg thiophene, or 1.4 kg amyl mercaptan per 83 m³ of liquefied propane.

Table 19/ HD5 Specification

Characteristics	Grade 1		Grade 2		ASTM Test Method
	Min.	Max.	Min.	Max.	
Propane Volume	90%	--	*	*	D2163
Propylene Volume	--	5.0%	*	*	
Butane & Heavier Hydrocarbons	2.5%	--	2.5%	--	
Vapour Pressure @ 37.8°C--	1435kPa	--	--	1435kPa	D2598/D1267 D2598/D2623
Motor Octane Number	95	--	--	--	
Sulphur (Lamp), mg/m ³ vapour @ 15°C & 101.325 kPa	--	230	--	345	D2784
Corrosion, (Copper Strip)	--	No.1	--	No.1	D1838

* Specified in supply contract [28]

The term "LPG" is often used synonymously with propane in North America. LPG in Europe (short for Liquefied Petroleum Gas) designates a fuel consisting of a mixture of propane, butane, and trace gases. Propane concentrations as low as 30% are common in some parts of Europe.

Propane has a boiling point of -43°C (-41.7°F). Its vapour pressure at this temperature is equal to atmospheric (101.3 kPa or 14.7 psia). Propane fuel systems do not use a fuel pump, but depend upon fuel tank pressure to deliver fuel to the engine. As propane temperature is reduced to its boiling point, delivery pressure drops below that required to sustain normal engine operation.

Propane vapour pressure increases steadily with rising temperature. As specified, propane vapour pressure at 37.8°C (100°F) is approximately 1435 kPa or 208 psig. This property necessitates the use of special storage containers, fuel handling equipment, and operating procedures to ensure safety.

Although propane's mass energy density (46.3 MJ/kg) is about the same as that of diesel fuel (42.9 MJ/kg), the practical volumetric energy density is lower than diesel for two reasons: first, the density of propane is only 0.51 kg/L compared to diesel's 0.84 kg/L (see Table 3); secondly, the propane tank may be filled only to the 80% level, to guard against spills due to thermal expansion of stored liquid.

The net propane energy storage is only about 53% of diesel's (18.9 MJ/L compared to 36.0 MJ/L for diesel). The conversion of vehicles to propane from diesel requires about double the space for fuel tanks if diesel bus range is required.

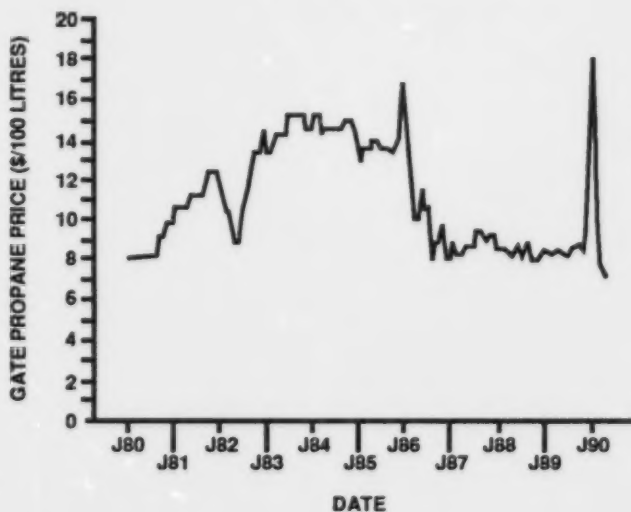


Figure 9/ History of Sarnia Gate Propane Price [29]

3.4.2/ Supply Infrastructure

There are currently over 1700 propane fuelling stations in Ontario. Propane suppliers are willing to provide on-site refuelling facilities at little or no charge to fleets that consume large volumes of propane.

Currently approximately 35% of Canada's propane production is exported to the U.S. Propane production totals about 150 000 barrels per day, and is projected to increase steadily to about 190 000 barrels per day by the year 2000 (Figure 10).

Figure 10 indicates the forecast demand for domestic propane. Current consumption by the transportation industry is approximately 12 000 B/D or about 12% of the domestic total. In Ontario, only about 1.5% of our transportation needs are satisfied by propane. Export propane could fuel up to 10% of Ontario's vehicles.

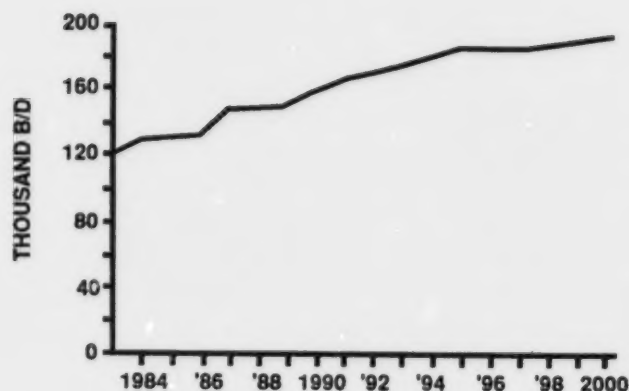


Figure 10/ Canadian Propane Supply Forecast [30]

3.4.3/ Industry Pricing Strategies

The retail price of propane in Ontario is directly related to the Sarnia "gate" price. The Sarnia gate is the eastern terminal of the Trans-Canada Pipeline, which supplies most of Eastern Canada's propane. Propane is shipped to bulk storage facilities throughout the province by tanker truck.

The net price of the fuel to the customer is dependent upon the gate price of propane, transportation, loading/unloading expenses, and profit margin. A 4.3¢/L provincial tax is currently charged at the retail level.

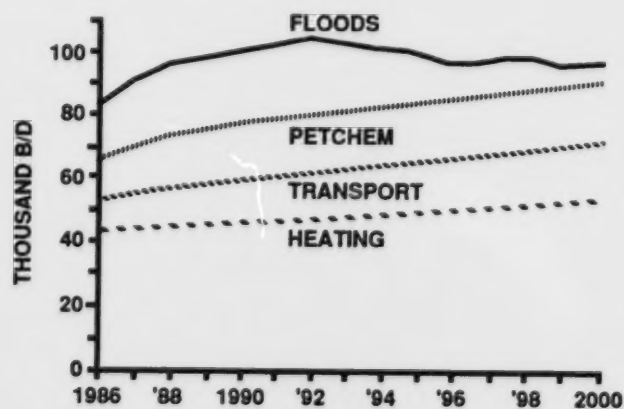


Figure 11/ Canadian Propane Demand Forecast [30]

The wholesale price of propane is dependent upon normal market forces of supply and demand, especially from the United States. Propane supply has been relatively constant since it is a derivative of natural gas production and petroleum refining. Propane

demand is seasonal; in the fall, crop drying results in significantly greater propane consumption. Spot shortages and resulting upward pressure on propane prices may be experienced.

The delivered price is also dependent upon annual consumption. Large consumers (in excess of one million litres annually) are offered attractive prices, since very large storage tanks capable of holding an entire tractor/trailer load of fuel directly from Sarnia may be installed, eliminating the intermediate storage part of delivery. The Sarnia gate price of propane has remained relatively constant over the past two years, averaging about 9.0¢/L (see Figure 9). Large users could expect to obtain propane for about 20¢/L, on site, tax included.

3.4.4/ Future Supply and Quality

Propane is obtained from natural gas wells and as a product of petroleum refining. Canada has large reserves of natural gas and petroleum, therefore the outlook for propane availability is currently very good.

However, the current propane supply is sufficient for only about 5% of Canada's transportation needs, and this proportion is not expected to increase. In addition, propane is a useful feedstock for the chemical industry, therefore there will always be competition for it, with the possibility of price instability.

Fuel grade propane quality is regulated by the HD5 specification which limits the concentration of constituents other than propane to 10% or less. Propane fuel quality is not expected to deteriorate in the future.

3.4.5/ Propane Technology

Propane engines are not currently available from bus and truck engine manufacturers. This situation is expected to continue until large orders of propane engines materialize. Until then, propane engines are obtained by converting existing diesel or gasoline engines of sufficient power to meet bus requirements. Most propane bus engines to date have been based upon conventional mechanical conversion equipment providing good durability and reliability at a reasonable cost. Components of a typical propane engine and fuel system are illustrated in Figure 12 [23].

Propane tanks are of robust construction because of the internal pressures that they must withstand in service. Tanks are equipped with pressure relief valves set at 3541 kPa (250 psig) if operated at temperatures up to 37.8°C (100°F) or 4419 kPa (312 psig) at up to 51.7°C (125°F). As indicated in Section 3.4.1, the propane tank requires about twice the volume of a diesel tank for a given total fuel energy.

The propane tank installed in the 40-foot propane buses at OC Transpo was constructed of four, 200 L tanks manifolded together. The tank was manufactured by Westeel-

Rosco Limited for transit bus applications. A water capacity of 800 L provided a 640 L usable fuel volume. Empty weight was about 318 kg (700 lbs).

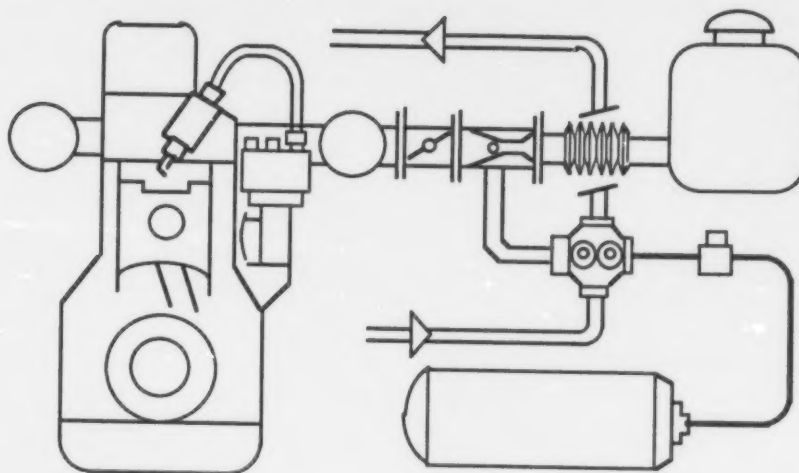


Figure 12/ Propane Engine Schematic Layout [23]

Two different tank finishes were assessed. The first was a typical propane tank finish sandblast, prime, and enamel paint. The second was sandblast, prime, and high solid white acrylic urethane finish. The urethane finish proved very satisfactory in terms of corrosion protection during the demonstration and would have been specified for additional conversions.

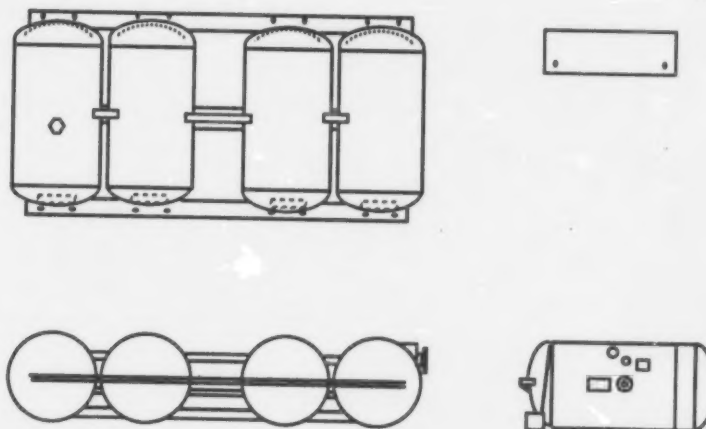


Figure 13/ Propane Tank Drawing

This tank's 640 L propane storage capacity has an energy content of 15 100 MJ (14.3 million BTU). By comparison, a 100 U.S. gallon diesel tank, typical of a 40-foot transit bus application, contains 14 000 MJ (13.3 million BTU).

The estimated volume of a 100 U.S. gallon steel fuel tank (including tank volume) is 380 L and for the OC Transpo propane tank assembly 1160 L. The diesel fuel tank energy storage density is about 36 840 MJ/m³ and the propane tank approximately 13 000 MJ/m³. Therefore in this particular case the diesel tank energy storage capacity is 2.83 times that of the propane tank.

The OC Transpo propane bus tanks were protected from salt spray and debris by screens fabricated from heavy expanded sheet steel. Fill and shutoff valves were remote-mounted enabling easy refuelling and tank shutoff.

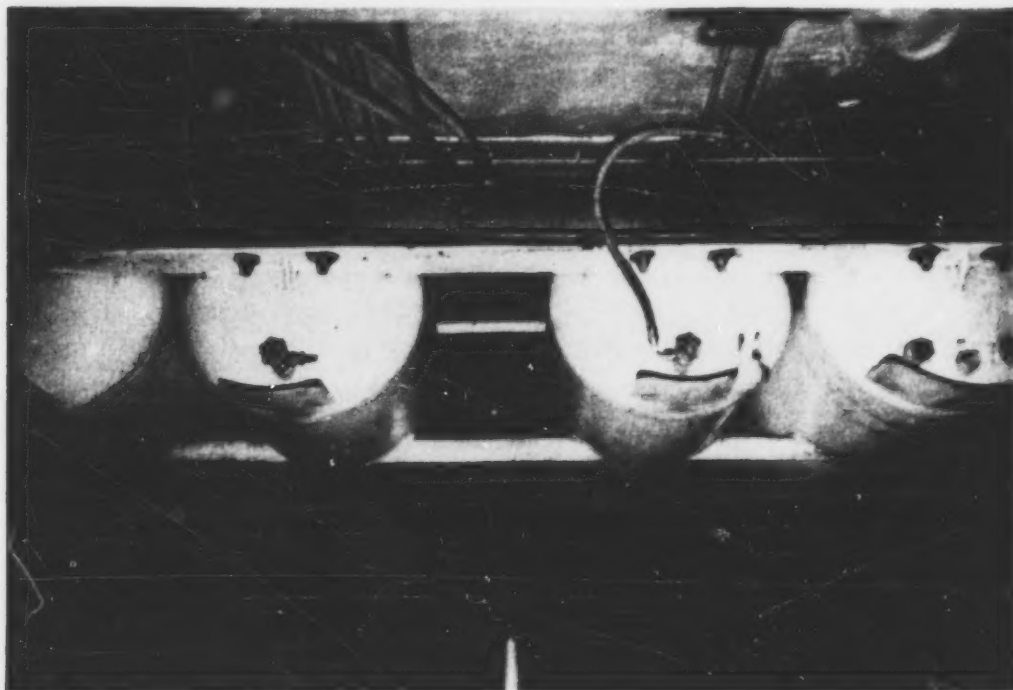


Figure 14/ Propane Tank Installation

Maximum bus range is transit operator specific and is dependent upon route length, route average speed, and the number of hours per day that the vehicle is in service. OC Transpo found that a range of 645 km (400 mi) was required to meet its needs. Table 20 lists particulars of the OC Transpo propane fuel system and refuelling time.

Further refinements are required to make propane hardware safer and more convenient for transit operators. The following is a brief description of proposed improvements.

Propane Bus Engines

The following is a review of several propane engines, which fall within the power range required by Ontario transit buses. Some of these engines were developed for stationary applications and are therefore not suited for highway use without modification.

Table 20/ OC Transpo Propane Bus Refuelling and On-Board Storage

Description	Magnitude
Average Fuel Economy	96.5 L/100km (2.92 mpg)
Maximum Range Required	645 km (400 m)
Maximum Fuel Load	621 L (137 g)
Average Daily Mileage	186 km (116 mi)
Average Fuel Delivery	180 L (39.6 g)
Maximum Refuel Time @	5 min
Minimum Delivery Rate	125 L/min (27.6 g/min)
Average Refuel Time	1.4 min

Caterpillar Stationary Engines

Propane versions of the Caterpillar 3306 and 3208 were developed. However, both were developed as stationary engines. Both engines are fitted with spark plugs and gas mixers. Both are available in two compression ratios: 8.0 (propane) and 10.5 (natural gas).

Because the engines were developed for stationary applications, they are not suited to the speed and load variations experienced in over-the-road applications. Refinement of the ignition, fuel, and governor systems and retuning for transient operation would be required to successfully operate these engines in buses.

MAN LPG Engine

Vienna Transport authorities have been operating LPG powered transit buses since about 1963. Currently approximately 400 buses are fuelled by LPG there. Vienna's newest buses are powered by the MAN G2566UH/UM, LPG engine.

This is an in-line six, four-stroke Otto cycle engine, with a compression ratio of 10.0:1. Mixture is electronically controlled (Landi-Hartog) incorporating an oxygen sensor and stepper motor driven mixer valve. The ignition system is a distributor type, and the exhaust system is equipped with a three-way catalyst.

Detroit Diesel Corporation (DDC) 8.2L

During 1982 and 1983, DDC developed a propane powered version of the 8.2 L, medium-duty diesel engine. The engine had 11.0:1 compression pistons, Delco electronic ignition system, Century propane fuel system, and special narrow spark plugs, which enabled the use of standard diesel cylinder heads.

The engine was dynamometer tested for about 200 hours and then torn down for inspection. The propane engine produced approximately 25% more power and torque than its diesel counterpart. Propane engine fuel efficiency was about 15% lower than that of the diesel and exhaust temperature peaked at 746°C (1375°F) compared to the diesel's at 593°C (1100°F). C (1100 F).

The engine was found to be in good condition upon inspection. Recommendations were made for relocation and recalibration of propane mixer, increased oil cooler capacity, and refinements to spark plugs and ignition wires. The propane 8.2 L engine has not been marketed.

DERECO/IVECO 8220 Propane Engine

The 8220 propane engine was developed by DERECHO of Switzerland from the IVECO 9.6 L diesel. A special reverse-rotation version of this engine (model 8220R) was also developed to satisfy the requirements of the GMC, V-drive configuration. This engine was supplied specifically for a propane bus demonstration program, which took place at OC Transpo.

Mercedes-Benz

Mercedes-Benz offers the OM 407 h and OM 447 h engine families running on LPG or NGV. These engines are all spark-ignition, inline six-cylinder configurations with 11.4 L and 12.0 L displacements, respectively. The OM 407 h produces 147 kW and the OM 447 h 150 kW (both at 2200 rpm) on gaseous fuels [23].

There is also a naturally aspirated NGV engine, the M 366 G, being developed for the South American bus market at Mercedes-Benz. This engine produces only 110 kW at 2800 rpm, however, and is unsuitable for North American buses.

Gaseous Mercedes-Benz engines differ from their diesel counterparts in a number of areas. Cylinder heads are cast to accommodate spark plugs instead of fuel injectors (water jacket must be considered) and intake ports are optimized for high volumetric efficiency, instead of high swirl rate. Iron head castings contain molybdenum and chromium to resist higher temperatures (similar to turbo-diesels). Valves and seats are made of special heat and wear resistant materials and are sodium-filled.

Compression ratios are set at 11.5 for propane, 9.5 for n-butane and somewhere in between these extremes for LPG, depending upon the relative proportions of propane and butane in the fuel.

The engine employs an automotive-type electronic ignition system with conventional distributor. Ignition timing varies with A/F ratio and accelerator pedal position. An electronic governor controls idle speed to anywhere between 450 and 600 rpm and limits maximum engine speed to 2350 rpm by closing the throttle plate. Gas to the mixer is cut off if the engine reaches a speed of 2500 rpm or if the ignition is shut off. The distributor, governor, and components for deceleration cutoff, and mixture control are assembled into a single module which replaces the diesel injection pump.

The gas mixer is of conventional design and incorporates two gas valves. These valves have been carefully optimized to ensure proper air-fuel ratio over the entire engine load/speed operating range.

The use of common DI diesel engine lubricants is not recommended for these engines since problems were experienced with combustion chamber deposits. A low ash lubricating oil is recommended.

GMC 454/427 V8

A medium-duty propane engine similar to the Chevrolet 454 cid engine may be purchased for approximately \$3500. This price includes only the basic engine and fuel system. Accessory components, exhaust system, cooling system, etc. must be mounted on the engine prior to its installation into the bus.

A 454 cid natural gas engine has been operated in a 30-foot OBI transit bus for over two years to date (Mississauga Transit). Two turbocharged 454s are in service in 40-foot OBI buses, operated by Command Lines in New York City. The same engine could be readily operated on propane in such applications, without major modification.

Cummins NTC 855

The Cummins 14 L, propane engine has been under development for about five years in a joint program with the Ontario Research Foundation (ORF), InterCity Gas, and the Ministry of Transportation. It is based upon a converted N14 (Big Cam) diesel block, which accounts for a large share of the heavy trucking engine market.

The engine is spark ignited (Ford Duraspark), turbocharged (Schwitzer turbo), and intercooled with a rated power output of 261 kW (350 hp) at 2100 rpm. The fuel system is Impco (200D mixer and two model E regulators), governor a Bosch RQ mechanical type, Air Research air-to-air aftercooler, and 8.5:1 compression pistons (modified from stock diesel).

Two engines operated satisfactorily in two class-eight highway trucks until December 1989, demonstrating reasonable reliability and fuel economy. The results of this demonstration are summarized in a published paper [31]. This engine would be acceptable for certain articulated bus applications, due to its larger size.

Selection of a Transit Bus Propane Engine

The most likely diesel engine candidate for conversion to propane will probably be four-stroke cycle, displacing about 10 litres and producing between 149 and 188 kilowatts (200 and 250 horsepower). Engines satisfying these criteria include the following:

- Caterpillar 3208 and 3306
- Cummins L10
- IVECO 8220
- Mack EM6
- Mercedes OM 407/447, and
- Volvo White TD101GB.

Diesel versions of these engines are typically priced in the \$10-\$15,000 range. It is estimated that propane engines could be produced in modest numbers (100-500 per year) at a cost of about \$18,000 to a large-volume user.

The predictions in Table 21 are based on diesel engine and estimated conversion costs for 1989 and the year 2000, by which time small-scale production prices may be in place.

Table 21/ Propane and Diesel Engine Cost

Description	Diesel	1989 Propane	2000 Propane
Base Diesel Engine	\$12,500	\$12,500	\$12,500
Injection/Governor System	\$ 2,500		
Propane Fuel System		\$ 500	\$ 500
Governor (Electronic)		\$ 3,000	\$ 1,500
Ignition System		\$ 1,000	\$ 1,000
Catalytic Converter		\$ 3,000	\$ 2,500
Per Engine Development Cost		\$10,000	
Net Engine Cost	\$15,000	\$30,000	\$18,000

The "per engine development cost" includes development of the engine system on an engine dynamometer, durability testing, engineering, and additional tooling to enable its manufacture. The largest single area of modification will be the cylinder head, which requires changes to the injector holes to accommodate spark plugs, and the replacement of valve seats (and possibly valves) with hardened components.

Exhaust Emission Systems Development

Properly assembled and tuned propane engines emit extremely low levels of hydrocarbons, carbon monoxide, aldehydes, particulates, and smoke. These levels are typically well within the 1991 EPA emission standards. Nitrogen oxide levels are typically comparable to other Otto-cycle engines. A propane engine with untreated exhaust produces unacceptably high nitrogen oxide emission levels.

3.4.6/ Propane Bus Maintenance

Spark ignition propane bus engines will probably require more frequent periodic maintenance than today's diesel counterparts. The ignition and fuel systems are likely to require the bulk of this work.

The most popular ignition systems available today incorporate a distributor, ignition coil, and a harness of ignition wires carrying high voltage electricity to the spark plugs. Distributors are prone to bearing wear and burned high voltage contacts. High voltage ignition wires are subject to insulation breakdown causing leakage and spark plug misfire.

The propane tank and fuel system require a periodic leak check and visual inspection for damage and corrosion. It is assumed that fuel system maintenance costs would be comparable to the diesel system.

Existing mixer-type propane fuel systems require periodic idle speed adjustments. They will also require rebuilding of the mixer and vaporizer at regular intervals. In addition, the propane fuel filter must be changed periodically, as are current diesel fuel filters.

3.4.7/ Propane Fleet Experience

The only major North American transit bus application of propane took place in Ottawa by OC Transpo.

OC Transpo

In 1982 an agreement was signed between OC Transpo, MTO (MTC at that time), and Eergy Mines and Resources Canada to institute a propane bus demonstration in Ottawa. The purpose of the demonstration was to demonstrate the practicality of operating a fleet of propane powered transit buses and to obtain information on reliability, operating costs, and public acceptance. Up to ten propane buses were run in revenue service alongside diesel powered buses for approximately four years.

The first 40-foot GMC bus was converted to propane in 1983. Performance, driveability, and fuel economy were determined before the commitment was made to the remaining nine conversions. The bus was track-tested in Ottawa in March 1984 using a modified Advanced Design Bus (ADB) fuel economy test cycle. The bus passed all performance goals (Table 22) and the decision was made to proceed with a full-scale demonstration.

Table 22/ OC Transpo Propane Bus Fuel Economy Targets and Results

ADB Test Fuel Mileage		
Trial	Propane	Diesel
1	3.09	5.12
2	3.12	5.28
3	3.03	5.39
4	3.09	5.31
5	3.11	5.20
Average	3.09	5.26

Target: Propane mpg/Diesel mpg = 1.8

Test Result: Propane mpg/Diesel mpg = 1.7

A total of 10 OC Transpo 40-foot GMC buses were retrofitted to propane, beginning in 1983. The buses were all 1979 model year, due to have their diesel engines overhauled at about the time of conversion. The first bus entered revenue service shortly after testing, followed by nine more over the following months.



Figure 15/ OC Transpo Propane Bus and Fuel Storage

An on-site fuel storage and dispensing facility was installed (Figure 15). A diagnostics tester and a supply of spare propane engine parts were purchased. Two mechanics were trained specifically on the maintenance of the propane engine by technical representatives from the engine supplier (DERECO of Arbon, Switzerland).

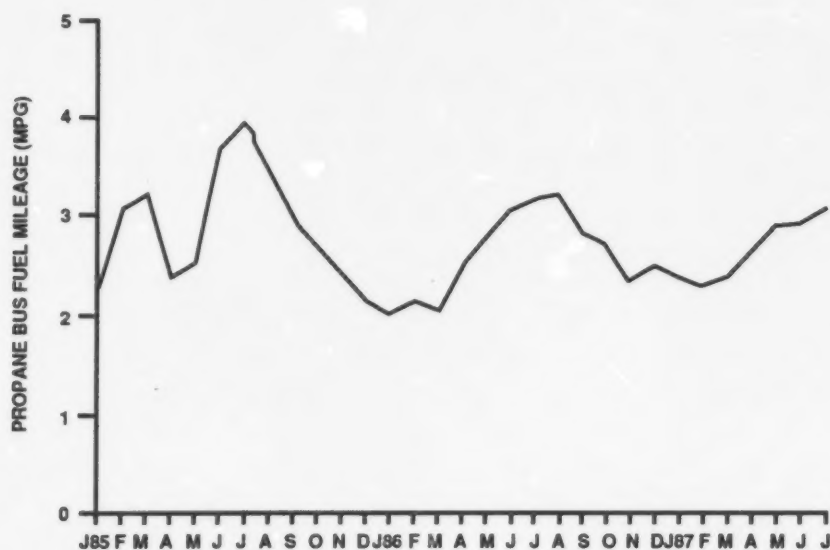


Figure 16/ Propane Bus Fuel Mileage

A passenger survey determined that patrons, for the most part, were indifferent with regard to their preference of propane versus diesel buses (very few noticed any difference at all). Drivers found that the steering was somewhat harder than the diesel bus, due to the extra weight of the propane tank in the front of the bus (power steering would have corrected the situation). Otherwise, the drivers preferred the quick response of the propane engine relative to the diesel.

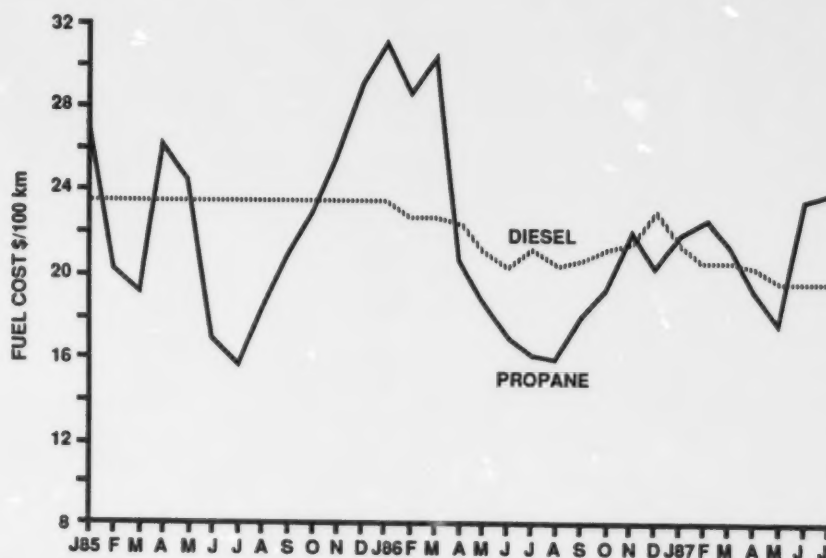


Figure 17/ OC Transpo Propane Bus vs Diesel Fuel Cost per km

Propane bus fuel cost was lower than the diesel, on a per mile basis, during the spring, summer, and fall. During the winter months, however, the propane buses were idled extensively on cold mornings to warm them up prior to entering service. This was due to the fact that the propane buses had to be stored outdoors at all times, because the bus storage facility had not been upgraded for propane vehicle storage. Extra winter idling considerably reduced the cost benefit of the propane bus relative to diesel.

Figure 16 shows the fuel economy of the propane bus over two years of operation. Figure 17 compares the average cost per mile of the propane buses to that of a sample of comparable diesel buses.

3.4.8/ Capital and Operating Costs

The capital and operating costs of propane buses and associated fuelling and garaging facilities are estimated in this section. Actual costs that are relevant to Ontario's transit operations are almost impossible to obtain because only one transit operator in the world has operated a significant number of propane buses for a long period of time Vienna Transit. Estimates have therefore been based upon what worldwide experience could be found and draws heavily upon the results of the OC Transpo (Ottawa) propane bus demonstration.

Table 23/ Propane Bus Capital Cost

Description	1989 Diesel	1989 Propane	2000 Propane
Bus Body	\$156,815	\$156,815	\$156,815
Engine	\$ 15,000	\$ 30,000	\$ 18,000
Fuel Tank/Line		\$ 3,000	\$ 3,000
Development		\$ 10,000	\$ 0
Bus Subtotal	\$171,815	\$199,815	\$177,314
P.S. Tax (8%)	\$ 13,745	\$ 0	\$ 14,185
Total	\$185,560	\$199,815	\$192,040

Vehicle Cost

Propane bus capital cost has been considered for:

- a current (1989) diesel bus for comparison;
- an OEM pre-production propane bus;
- an OEM production propane bus (typical of mature technology in the year 2000).

The following assumptions have been made regarding the propane buses:

- buses incorporate domestic (North American) engines and transmissions;
- initial cost is high due to the small number of vehicles being produced and considerable development costs;
- as production of the bus continues at close to diesel bus rates, the price will approach that of the diesel-powered bus (year 2000 propane);
- a heavy-duty transit diesel engine is the basis of conversion, incorporating a spark-ignition system, and 100% propane fumigation or port injection.

The engine and fuel system related capital costs for a typical diesel and propane transit bus are detailed in Table 23. It has been estimated, in the industry, that a pre-production propane engine will cost about \$30,000 (Table 23) and that this price will gradually drop to \$18,000 as production approaches diesel production levels. Fuel tanks and delivery hardware will cost approximately \$3000 – relatively constant over the 10-year period, because this technology is already relatively mature. A \$10,000 per bus development cost will be borne by early production buses for work associated with the design, testing, and refinement of the bus. The \$10,000 per bus development cost would almost certainly be reduced to zero over ten years of bus production.

Overhead Equipment Costs

Equipment required to operate propane transit buses consists mainly of bulk fuel storage and dispensing equipment as well as upgrading of bus maintenance and storage facilities.

Bulk Propane Storage and Refuelling Facility

To properly specify a bulk propane storage and dispensing facility, certain information must be known about the planned propane bus fleet. The total number of buses,

average daily fuel consumption per bus, and maximum permissible refuelling time must be considered. The required number of days of refuelling per bulk fill must also be considered.

If a propane bus fleet is replacing a diesel bus fleet, propane bulk storage may be sized relative to the original diesel bulk storage. For a 250-bus fleet, diesel bulk storage totaling 90 720 L (20 000 imperial gallons) is required.

The average recorded fuel economy of the OC Transpo propane buses is used as a basis, at 96.5 L/100km (2.92 mpg), relative to average diesel fuel economy of 53.7 L/100km (5.25 mpg). According to these figures the propane bus requires 80% more fuel, by volume, than the diesel to cover a given distance.

Thus a total propane storage capacity of 163 296 L (36 000 imp. gal) will be required. Actual storage capacity will be 25% greater still to allow for the 80% fill limit for propane fuel tanks. Therefore a propane storage tank displacing 204 120 L (45 000 imp. gal) must be specified for a 250-bus fleet.

The estimated cost of the refuelling facility, including two dispensers, two fuelling islands, two pumps, foundation, piping, control system, impact protection, and electrical power supply is \$500,000. The cost per bus is \$2,000. These costs would be realized by the transit operator prior to the first year of operation.

The bulk propane storage facility has a requirement for periodic inspection, maintenance, and repairs. A sum of \$2000 annually was arrived at on the basis of an inspection every two months for approximately six hours per inspection (\$56/hr). Maintenance cost estimates were also made for the facility (Table 24), totalling \$4000/year. Annual operating costs of \$6000 averages \$24 per bus, based upon a 250-bus garage.

Table 24/ Propane Storage and Dispenser Facility Operating Costs

Maintenance	Details of Work	Annual Cost (\$/yr)
Inspection	\$2,000 / year	\$2,000
Painting	\$1,500 every 3 years	\$ 500
New dispenser hose	1 each year @ \$200	\$ 200
New dispenser nozzle	1 each year @ \$200	\$ 200
Annual calibration	\$600 every year	\$ 600
Pump rebuild	\$1,200/10,000,000 L	\$1,000
Dispenser rebuild	\$1,800/10,000,000 L	\$1,500
Total Cost		\$6,000
Total per bus*		\$ 24

* based on a 250-bus fleet

Bus Maintenance and Storage Facility Upgrade

In the preparation of facilities to store and maintain propane buses, certain equipment must be upgraded to operate safely in the event of a gas leak. Minimum ventilation standards must be attained and a protective hydrocarbon detection system installed.

Garage modifications include the replacement of conventional electric motors with an "explosion-proof" type, the upgrading of circulating fans to provide an adequate number of air changes per hour within the building, and the replacement of any open flame type equipment (such as gas-fired furnaces) with equipment approved for operation in an explosive environment. The estimated cost to perform the garage modifications proposed is \$1.0 million for a 250-bus garage (\$4000 per bus).

A suitable hydrocarbon detection and alarm system must also be installed to detect gas leakage in the garage. Ideally hydrocarbon gas sensors would be placed at strategic locations in the facility (such as near the floor along bus storage lanes, in drainage ducts, and inspection pits). In addition to providing an audio and visual alarm in the event that gas is detected, the system would identify which area of the garage the leak was detected in. As an extra precaution, the natural gas supply to the building could be shut off as well.

Regular maintenance and testing of the hydrocarbon detection and alarm system will probably be required. Annual inspection costing an estimated \$25,000 would be necessary (\$100 per bus/year). These costs are summarized in Table 25.

Table 25/ Propane Bus Maintenance and Storage Facility Cost Estimates

Requirement	Capital Costs	Annual Cost
Garage modification	\$ 800,000	
Gas detection system	\$ 200,000	
Gas detection system maint		\$25,000
Total Cost	\$1,000,000	\$25,000
Total Cost (\$/bus)*	\$ 4,000	\$ 100

* based on a 250-bus fleet

3.4.9/ Bus Operating Costs

Fuel Cost

Medium and large transit bus operations, as well as some smaller properties, with all buses running on propane, would qualify for very competitively priced propane (see Section 3.4.1). The propane supplier will often install and maintain a propane storage and refuelling facility on-site for large users at 20¢/L, including 4.3¢/L provincial tax.

Propane priced at 20 ¢/L equates to an energy cost of about 0.85 ¢/MJ compared to diesel at 1.08 ¢/MJ. Significant fuel cost savings may be realized even though more propane per mile is typically consumed.

3.4.10/ Equipment Availability

At this time, there are no known suppliers of bus-sized propane engines, aside from those engine manufacturers which have developed such engines to a prototype, or test stage. A rather large order, or considerable commitment in terms of total engine purchases, would be required to interest most engine builders enough to cause them to enter the propane bus engine market.

Propane bulk delivery and storage, as well as bus-mounted fuel storage and delivery equipment, is readily available from a number of suppliers at reasonable cost. Equipment to upgrade maintenance facilities is also readily available.

A well supported (by its manufacturer) propane engine is the key to successfully operating a fleet of buses on propane. Without this support, it would be virtually impossible to operate 250 propane buses on an ongoing basis without major operational problems.

3.5/ Electricity

3.5.1/ Energy Characteristics and Availability

Electricity is not strictly a source of energy: it is an effective means of transmitting and controlling energy. The electric generator, and the total electrical delivery and control system from the energy source to the electric motor, takes the place of the transmission in an internal combustion engine powered vehicle.

Electrical generating capacity in Ontario has typically exceeded demand, up until the past few years, resulting in surplus power which has been sold outside the province. Lately though, particularly in very hot or cold weather, electrical supply has reached the point of just barely being able to cope with demand. Thus even in Ontario the fact remains that electrical generating capacity is finite and not always in surplus, as was the case in the past.

Electricity cost in Ontario, to industrial users, is typically 6.6 cents per kilowatt hour, at the electrical utility's meter. This cost translates into an energy cost per kilometre of 19.3 cents (Table 26) for electric trolleys.

3.5.2/ Status of the Trolley Bus Technology

The basic trolley bus, for the purposes of this report, refers to an electrically powered, rubber-tired bus, of similar interior and exterior dimensions to those of the diesel bus, but

Table 26/ Electricity Versus Diesel Energy Cost

Description	Electricity	Diesel 89
Unit Cost (\$/100u)	\$ 6.60	\$37.0
Energy Cost (\$/100MJ)	\$ 1.83	\$ 1.03
Energy Mileage u/100km	292	53.7
Energy Cost \$/100km	\$19.3	\$19.9

u - units, kWh-electric, litres-diesel

with an electric motor, electric power collector system, and power control unit (PCU) in place of the engine, transmission, and fuel system.

Externally, the trolley bus has not changed very much in the past 30 years. Power is supplied at 600 volts DC, through roof-mounted poles from a twin wire, overhead supply. Internally, however considerable change has taken place in the design of the trolley propulsion system.

Early trolley bus propulsion packages incorporated a 600 VDC electric motor, and a simple contactor-type power controller. Contactors control current, through a bank of resistors, to the motor. The driver's input command triggered the appropriate contactors (high current switches), routing current through the required resistors to the motor. Motor torque was therefore controlled in steps, providing a relatively jerky ride. Energy efficiency also suffered, due to resistance losses and the motor required periodic brush servicing.

The main advantages of such a system was that it was simple, and simple to repair. The cost of the propulsion system was approximately the same as the engine and transmission, therefore bus costs were similar.

Electronic motor speed controllers have become smaller, cheaper, and more reliable since the early 1970s. The electronic speed controller conditions the power to the motor by chopping it into on/off pulses (such controllers are called "chopper controls"). By varying the ratio of on-to-off time per pulse, motor power is controlled. Since the pulse frequency is typically several hundred Hertz, variation in motor load is much smoother than with contactors. Brush maintenance is still required on an ongoing basis, as the motor is the same type used in the contactor-controlled trolleys.

More recently, the use of AC electric motors (brushless) in trolleys has become an attractive alternative to the DC motor. These motors are the same units that have been used in industry for years now, with very high reliability. They have not powered trolley buses until recently due to the lack of a reliable, light-weight DC-to-AC inverter/PCU systems. Such a system has all the advantages of the chopper controlled PCUs and the low maintenance cost of an AC motor.

3.5.3/ Capital Cost

Trolley Bus

As mentioned in the previous section, the capital cost of trolley buses was at one time very similar to that of conventional diesel buses (Figure 18). However, over the last ten years the price of the trolley has taken off relative to that of the diesel bus. Several factors are responsible for this large price difference. Diesel bus technology has not changed significantly over a long period of time. Consequently, not much effort and money has been spent on engineering, constructing, and integrating new components. Bus manufacturers have also been able to purchase and use truck components, which are made in large numbers and are, therefore, less costly. In addition, intense competition among a relatively large number of North American bus manufacturers for a rather small and stagnant market has contributed to relatively low diesel bus prices.

In contrast, trolley bus propulsion systems have seen significant changes over the last decade. The changes in the power control unit have been revolutionary, necessitating new engineering and systems integration at a substantial cost. Most of the trolley power train components are unique and are custom made. They are certainly not common

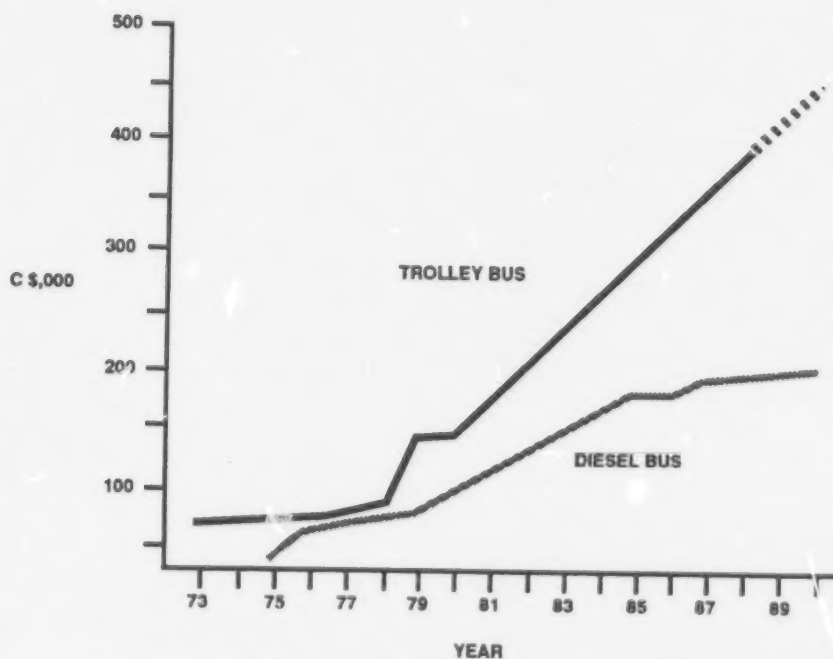


Figure 18/ Diesel vs Trolley Bus Cost [32]

with large volume production vehicles such as buses. Furthermore, the trolley bus has additional component requirements for power pickup, auxiliary power, insulation, etc., which add to the manufacturing cost. All these additional costs have been compounded by the fact that in North America only a small number of trolley buses have been ordered over the last decade. The small number of units bear the larger cost of development, engineering, and manufacturing resulting in higher trolley bus prices.

Table 27/ Trolley Bus Capital Cost

Description	1989 Diesel	1989 Trolley
Bus without engine/motor	\$156,815	\$156,815
Engine/Motor	\$ 15,000	\$ 20,000
Power Controller , trolley poles, etc.		\$200,000
Eng'g & Dev'mnt		\$ 50,000
Bus Subtotal	\$171,815	\$426,815
P.S. Tax (8%)	\$ 13,745	\$ 0
TOTAL	\$185,560	\$426,815

PCU and other electronic equipment installed in a modern trolley bus adds considerable cost (since these are often custom, low-volume items) and complexity to the trolley bus propulsion system. This factor also impacts on the maintenance cost, since problems typically take longer to diagnose and repair.

The bottom line is that a typical, baseline trolley bus costs more than double that of comparable diesel-powered equipment. Add to this the cost of additional equipment to overcome one of the trolley's most serious limitations capability. APUs (auxiliary power units) consisting of a diesel engine coupled to an electric generator are becoming increasingly popular on trolleys. These units provide flexibility to trolley buses, however at a significant capital and operating cost.

Overhead System

The cost of the power distribution system is very difficult to estimate. Recent bids are very scarce and there is an understandable reluctance to discuss the cost over-runs on recently completed works. The conditions on the chosen route can significantly increase the cost especially where there is some uncertainty about the conditions under the road surface. A figure of \$1.53 million/km of two-way route is used in this report, which is based upon a recent estimate by TTC.

Other factors that must be considered in the overhead capital cost estimate are whether existing overhead already exists and to what extent this overhead requires refurbishment and/or expansion. In addition, the probable life of the overhead wiring and substations must be estimated. This infrastructure typically lasts much longer than the vehicles operating on it. For the purposes of this study, a life equivalent to two bus lives (i.e., 36 years) was assigned to new overhead.

In the case of the trolley bus, the ratio of buses to overhead distance is very important in the determination of overhead capital (and operating) costs, on a per-vehicle basis. As shown in Figure 19, overheads are typically in the range of 0.6 to 3.5 kilometres (0.4 to 2.2 miles), one way, per bus. The average ratio for Canadian trolley bus operators is 1.21 km/bus (0.75 mi/bus).

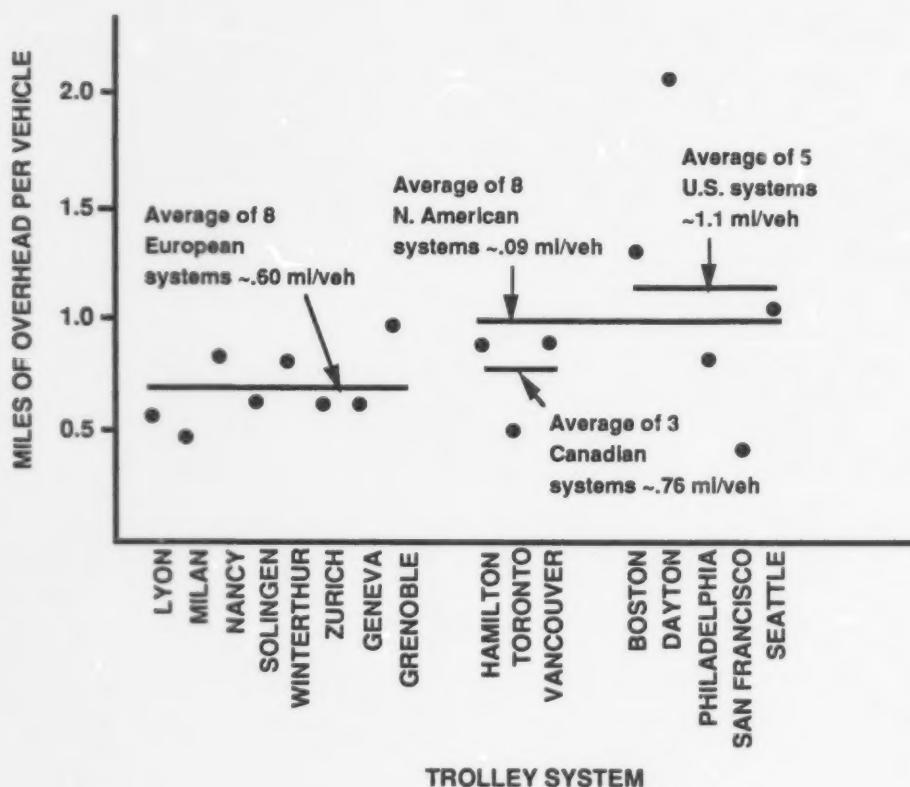


Figure 19/ Overhead Wire Length per Trolley Bus [33]

The overhead capital cost estimate of \$1.53 million per route kilometre (two-way) results in a per bus cost of \$925,650 (Table 28), if this overhead were to be replaced in its entirety. This scenario does not apply to established trolley routes with overhead in good condition; however it provides an estimate of overhead equipment prices for a typical new or replacement system. In order to account for the longevity of the overhead system, a residual value of \$462,825 is applied in the economic analysis, representing the remaining useful life of the overhead system at the end of the (first) bus life.

The per-bus overhead capital cost is inherently sensitive to the length of overhead per bus. For this report, the Canadian average of 1.21 km of overhead per trolley was adopted. Reduction of this distance to 500 metres, which corresponds to a headway of 1.5 minutes at an average vehicle speed of 20 km/h, would reduce the overhead cost per trolley to \$382,500.

Table 28/ Trolley Bus Overhead Costs

Capital	Operating
1-way Overhead/trolley (Can) 1.21 km	Overhead maint./trolley \$6,000
2-way Overhead/trolley (Can) 0.61 km	
Overhead cost per 2-way km \$1,530,000	
Overhead cost per trolley \$925,650	
Overhead residual/trolley* \$462,825	

* after 18 years

3.5.4/ Operating Cost

Trolley Bus

Recent studies of trolley and diesel bus maintenance costs have not shown any significant difference between them. Therefore, for the purpose of this study, identical maintenance costs were used for the trolley and 1989 diesel bus. The trolley, however, still has to bear the maintenance costs associated with the overhead wire and substations, which adds a considerable burden to its total operating cost.

Experimental alternatives to the electric trolley, such as the battery bus, presently cost significantly more than the trolley while fuel cell-powered buses require considerably more development. For these reasons, these propulsion systems are not considered in comparing electric systems with the other alternative fuel systems.

Overhead System

An annual maintenance cost for the trolley overhead system based upon a TTC estimate has been used for this study. The figure provided averages \$6,000 per bus, per year. This covers repairs to overhead wires, supports, poles, and substation equipment.

3.5.5/ Equipment Availability

The electrical equipment needed by the trolley bus is readily available in Europe and North America. However, most of these components are made on order in smaller numbers. Availability of spare parts has been a problem with the changing components which suppliers cannot be expected to stock.

3.6/ Dual-Mode Bus

The dual-mode bus has the capability of using at least two basic power supplies. While many different combinations may be possible, in practice, the only revenue service dual-mode bus being used today is the trolley/diesel. The main justification for using this combination is the need to avoid pollution in sensitive areas such as downtown central business districts that have high density traffic, or where tunnels are required to ease downtown congestion.

No trolley/battery bus has yet passed beyond the prototype stage mainly because of the capital and maintenance costs of the battery. This discussion will therefore be confined to the trolley/diesel dual mode buses.

In Nancy (France), where there are severe downtown pollution problems due to high traffic densities, the trolley mode contributes to the solution of the pollution problem and runs as a diesel in the lower density outer areas. A tunnel was required in downtown Seattle (U.S.A.) to reduce traffic congestion and because the ventilation of this tunnel proved expensive, an alternative lower cost solution was found in the dual-mode bus, which runs as a trolley in the tunnel.

Trolley buses tend to be more costly than diesel buses due to the extra cost of the overhead wire and the power supply system. As the number of buses per kilometre of route is reduced the extra cost borne by each bus rises significantly. This means that the trolley bus tends to become even more costly as the route moves away from the city centre. Depending on the total route configuration however, the dual-mode bus may provide a less costly solution than the pure trolley bus, especially if the overhead wiring is confined to the routes with high bus densities.

3.6.1/ Status of Dual-Mode Bus Technology

In general the dual-mode trolley bus can be provided with all the same electrical equipment as the pure trolley bus. The only question to be dealt with is how the diesel engine is applied to the system.

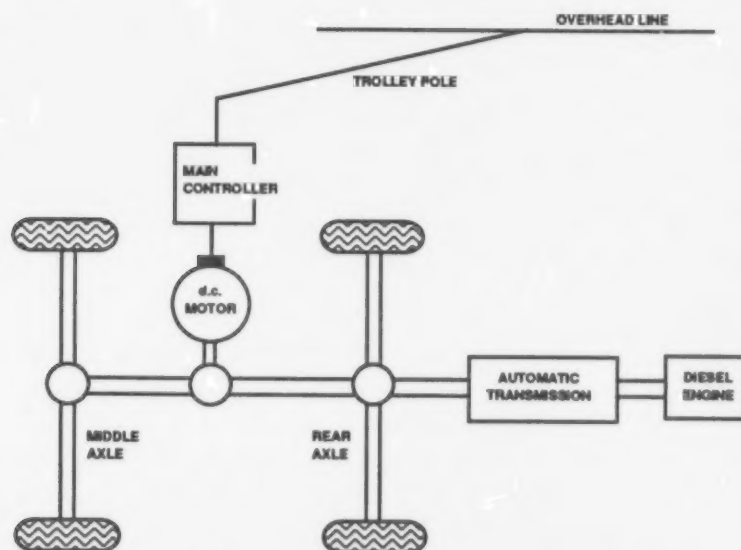


Figure 20/ Renault Dual-Mode Bus Driveline Arrangement

The Nancy bus was developed by Renault and happens to be an articulated bus. The articulated bus is better suited to the dual-mode concept because there is more space and an extra load-carrying axle to accommodate the extra equipment needed. The Renault arrangement is shown in Figure 20, which shows the electric drive motor connected to the main drive shaft by a right angle gear box.

The Breda/Westinghouse drive arrangement is shown in Figure 21. In this case the drive systems drive separate axles, which allows a simple mechanical arrangement. This system would only apply to three-axle buses.

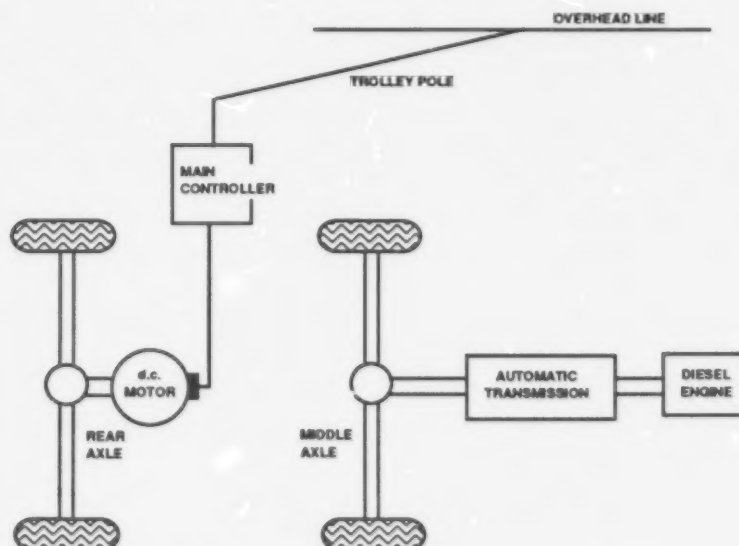


Figure 21/ Breda/Westinghouse Dual-Mode Bus Driveline Arrangement

The MAN company in Germany has developed a trolley/diesel bus which is being used in Essen Germany. The drive arrangement is shown in Figure 22, where the electrical and diesel drives enter the differential of the third axle through clutches. The clutches and gears are integrated into a neat single housing.

An interesting arrangement, shown in Figure 23, has been developed by Neoplan and Garrett where the power of the diesel engine is converted to electrical power by means of an AC generator. In effect the generator/controller/motor as a combined unit acts like a variable speed transmission and also allows for the change to trolley operation to be done electrically. This arrangement has not yet seen revenue service although a prototype has been built and demonstrated.

In general, the dual-mode system will allow many different combinations of power sources and processors. The above list, however, indicates those that are actually in service or show promise of reaching revenue service shortly. All the buses mentioned above are three-axle articulated units.

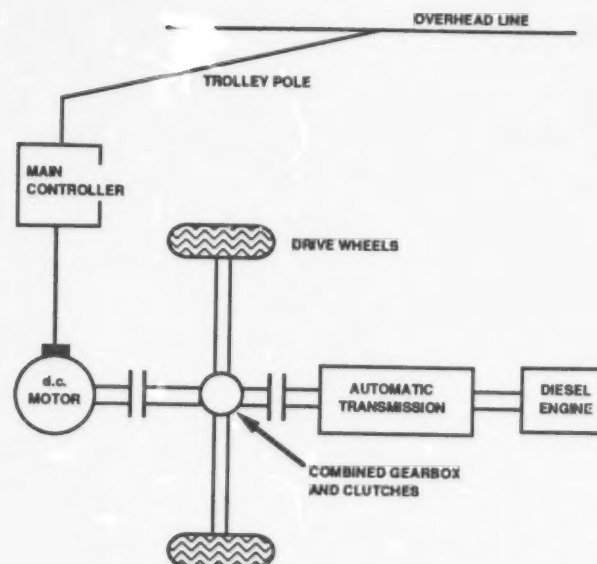


Figure 22/ MAN Dual-Mode Bus Driveline Arrangement

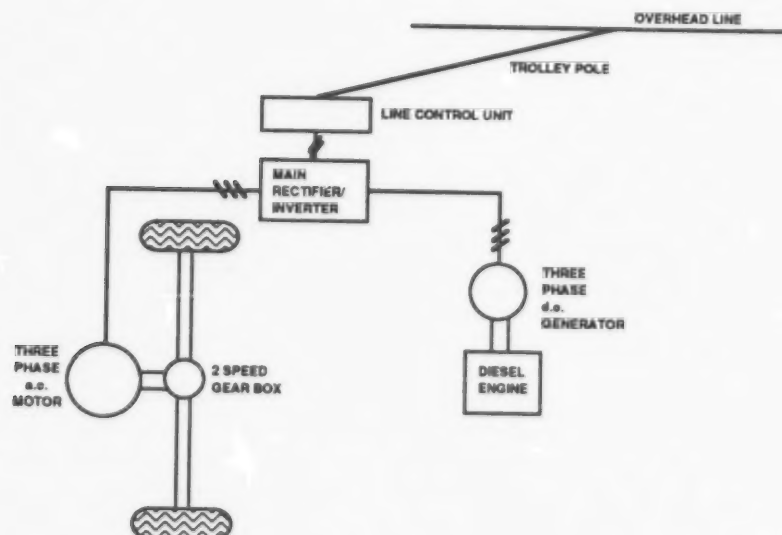


Figure 23/ Neoplan/Garrett Dual-Mode Bus Driveline Arrangement

3.6.2/ Equipment Availability and Cost

In North America, dual-mode buses are in use in Seattle and have been ordered for San Francisco. The Seattle buses cost \$478, 593 U.S. in 1990, while the San Francisco units will cost \$651,183 U.S. and delivery will start in 1993. The designs used in these articulated dual-mode buses are unique. It will take a while for the transit industry to agree upon a standard propulsion package for dual-mode buses in the foreseeable future.

3.7/ Hybrid Electric/Natural Gas Bus

In 1990, MTO started a co-operative project with OBI and a number of other contractors and financial backers to develop a hybrid electric/natural gas bus. In this project, a hybrid powertrain concept will be employed whereby a restricted speed natural gas engine (optimized for exhaust emissions) generates the necessary electrical power to drive the bus via underfloor-mounted electric motors.

Due to the small size of the electric motors, the bus floor height can be reduced, which in turn enhances accessibility. An array of electrical storage batteries will be used to provide power during vehicle acceleration and other peak power demands such as hill climbing. Thus, the natural gas engine can be smaller than would otherwise be necessary, which will result in lower exhaust emissions and improved fuel efficiency. The batteries will be recharged by regenerative braking and by the engine/generator during periods when full power is not being used to drive the vehicle.

4/ ENVIRONMENTAL AND SOCIAL IMPACTS

The main impetus for considering alternative fuels for transit buses at the present time is the obvious negative environmental impacts associated with the continued use of diesel fuelled vehicles as they are now designed. Prominent among these are visible smoke, odour, and noise, all of which are particularly objectionable in urban environments. By 1991, all new engines to be used in transit buses will have to meet stringent new standards. The engines that are eventually supplied will either use upgraded diesel technology or rely on alternative fuels. There will be many secondary consequences involved in adopting new and unfamiliar fuels and Table 29 shows a comparison of some of these. They may be considered under the headings of local and global impacts.

Table 29/ Health and Environmental Factors in Handling Alternative Fuels*

Fuel Type	Diesel	Gasoline	Methanol	Propane	Natural Gas
Description	Class 2, liquid	Class 1, liquid	Class 1, liquid	Low pressure liquid and gas	High pressure gas
Storage Arrangement	Underground tank	Underground tank	Underground tank	Above ground tank	Underground line, above ground tanks compressors
Fuelling Location	Inside	Outside	Outside	Outside	Outside
Health Hazard from Leaks					
- Atmospheric	Very low	Moderate	Moderate, TVL >1000 ppm	Low, TVL >1000 ppm	Low, TVL >1000 ppm
- Accidental Ingestion	Very low	Low	High (unless denatured)	Zero	Zero
Environmental Hazard	Non-dispersible with water, Biohazard, non-degradable	Non-dispersible with water, Biohazard, non-degradable	Dispersible with water, Bio-degradable	Low risk	Low risk

* Effects of combustion emissions not included

4.1/ Local Impacts

Diesel fuel is a liquid of low flammability that is stored easily in underground tanks and safely dispensed in sheltered areas. Current garage practices for transit properties have evolved around these facts. Vehicles are fuelled, idled, and parked overnight in enclosed garages. Heavy maintenance work, involving hazardous operations such as cutting, welding, grinding, and the use of impact tools, is safely carried out on vehicles with full tanks and close to fuel lines. Potential ignition sources – unenclosed electric motors and lamps, sparks, and matches – create little risk and work in confined areas, such as pits with little ventilation, is accepted by personnel.

All the alternative fuels are more volatile and flammable than diesel fuel. This will increase the potential for fires, explosions, and exposure to fuel vapours, as described in the following sections.

4.1.1/ Static Fire Hazard

The main factors contributing to the hazard from fire are: volatility, flammability range, ignitability, persistence of flammable vapours before ignition, heat output, heat radiation, flame visibility, and ease of suppression. The report, "Gaseous Fuel Safety Assessment for Light-Duty Automotive Vehicles," [34] includes a comprehensive evaluation of the hazard from gaseous and petroleum fuels but does not consider methanol. A 1982 DOE report (referred to in ref. 35) compares all fuels except natural gas. In another report [36] all the alternatives are compared but diesel is not included. A 1986 EMR report [37] considers the safety implications of methanol from a Canadian perspective.

Figure 24 gives an approximate ranking of the various individual factors affecting the risk of fires or explosions. It is based on a number of references (particularly [34]). For the purpose of including methanol with the other data, M85 is assumed to have the same vapour pressure as gasoline while M100 is less volatile. Volatility is likely to be the dominant factor in contributing to a hazard. However, the ease of dispersal of the lowest density fuel, NG, partly compensates for its greater volatility and higher pressure so that the hazard in poorly ventilated spaces is judged to be greatest for propane. Methanol is on the whole less hazardous than gasoline or the gaseous fuels, partly because of its lower volatility, greater auto-ignition temperature, and lower heat content. Though theoretically the air/vapour concentration above the liquid level in tanks containing M100 is within the flammable range at ambient temperatures, in practice it is hard to ignite at the filler end of a container and the flame front is easily quenched by the filler pipe. The lower electrical resistance of the fuel also minimizes the risk from static electric discharge – a significant risk in the handling of bulk petroleum fuels including diesel. Methanol is, however, anomalous in terms of surface ignition. Transport Canada [38] has compared methanol and gasoline for several safety related parameters. It was found that methanol has lower surface ignition energy and would ignite as a liquid on a very hot manifold (675°C) under conditions when gasoline did not. This might indicate an increased risk factor during a crash.

The main remedy for all the alternative fuels is to greatly increase ventilation whenever vehicles using such fuels are operating in confined areas. This, coupled with revised operational practices, should keep workplace hazards within acceptable limits.

4.1.2/ Crash Induced Fire Hazard

Statistics of accidents involving alternative fuelled vehicles have been examined but the data are too sparse and the reporting standards too variable for a firm conclusion to be based on field experience. However, the safety record for propane and natural gas is considered good compared to gasoline, based on many years' experience in Europe.

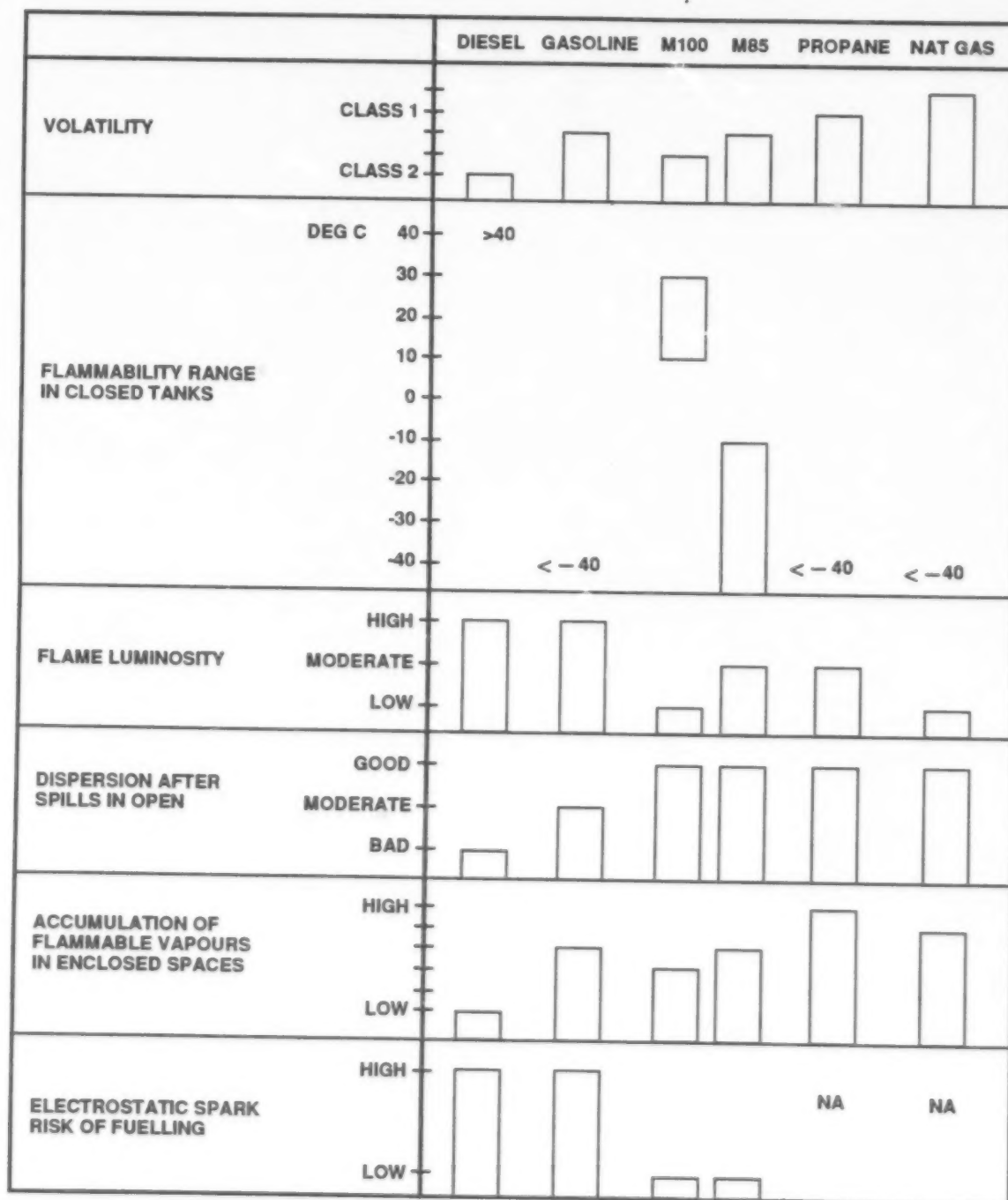


Figure 24/ Comparison of Various Hazard-related Fuel Properties

A number of studies have looked at the tested crashworthiness of alternative fuelled vehicles [e.g., 34, 39, 40 and 41]. The advantage gaseous fuels have in crash situations is due to their confinement in strongly made pressure vessels. Such tanks retain their integrity under conditions in which a gasoline or diesel tank would be torn open. In some cases gaseous fuel was released from severed lines and fires sometimes resulted but explosions of the type often observed with gasoline due to sudden release from a ruptured tank were not observed. Sealed high pressure tanks are subject to another mode of rupture – that due to prolonged heating from an external fire leading to a B.L.E.V.E. (Boiling Liquid Expanding Vapour Explosion). Though the eventual release of energy can be severe, the hazard is mitigated by the time taken for temperatures and pressures to reach the critical values. Appropriate fire-fighting actions before this point are likely to diminish the possibility of this event in most automotive collisions. However, the risk is more serious when large tanks – stationary or mobile – are involved and catastrophic accidents of this type have occurred, involving rail tankers for example.

Los Alamos National Laboratory performed an analysis [34] of various collision situations (e.g., rural, urban, and in a tunnel with light-duty vehicles) and estimated relative frequencies of occurrence of various hazardous events was given. Methanol was not considered in the analysis but it is basically equivalent to gasoline. The analysis is modified according to the differences mentioned in Section 4.1.1 above, e.g., lower or equal vapour pressure, less heat release and radiated heat transfer, lower flame visibility, yet in certain circumstances, greater ease of ignition on very hot surfaces. In a rural-type, high-speed collision with plenty of room for dispersion by air, the risk of fire following line rupture is considered to be similar for alternative fuels and gasoline. For explosions, the risk is again comparable for gasoline (and, presumably, methanol), propane and CNG. In an urban collision, which is supposed to take place at lower speeds but with the added complication of nearby vehicles, the risks of fire and explosion are similar to those in rural collisions. Hazards are least likely for diesel in all situations because of its low volatility and difficulty of ignition.

4.1.3/ Toxic Hazard

Methane is physiologically inert. Propane is also relatively inert with a Threshold Limit Value (TLV) of 1000 ppm. Both gases would, of course, cause suffocation at very high concentrations. However, as they are artificially odorized to aid detection, and as the flammability hazard is more dominant, any possibility of direct adverse physiological effect from these gases may be considered negligible. The liquid fuels, on the other hand – diesel, gasoline, and methanol – are all in various degrees poisonous in common with most organic liquids.

The reason for considering toxicity particularly, in the context of alternative fuels, is a perceived risk involving methanol. This perception probably has arisen because of many reported accidental poisonings in the past occurring because of confusion of methanol with common alcohol found in alcoholic drinks. As methanol, under the name of methyl hydrate, is freely available in hardware stores and as the methanol that would

be used in buses would be denatured to some extent with additives and would not be pleasant to drink, deliberate consumption from this source is unlikely.

By direct ingestion, methanol can be fatal down to a few tens of cubic centimetres (0.5 to 1 ounce) while the usual fatal dose is between 50 and 100 cc [42]. This is no more toxic than gasoline or diesel fuel, which, however, are unlikely to be drunk deliberately. Liquid fuels can also be absorbed by skin exposure and by breathing vapour. Below is listed the TLVs for methanol, gasoline, and some gasoline blending components.

Table 30/ Threshold Limit Values

Component	Methanol	Benzene	Toluene	Gasoline
TLV, ppm	200	5	80	200*

* Calculated, assuming zero benzene

Source: Swedish Motor Fuel Technology Co. [43]

Animals exposed to very high concentrations of methanol vapour, e.g., up to 5000 ppm have shown only minor toxic effects [44] so that the TLV value of 200 ppm is conservative. Methanol is inactive genetically in contrast to many gasoline components, e.g., benzene, which is carcinogenic. Both methanol and liquid hydrocarbons can be absorbed through the skin. This can cause dermatitis and eventually the same symptoms of poisoning as if the liquid had been ingested. Methanol gasoline blends are considered to be more aggressive in this respect than either of the components alone.

Assessments have been made of the overall toxicity risk associated with methanol and hydrocarbons.

Table 31/ Comparative Toxicity Ratings, 1 = Mild, 5 = extreme

Component	Eye Contact	Inhaling	Skin Absorption	Skin Irritation	Ingestion
Gasoline	2	3	3	1	2
Methanol	2	2	2	1	1

Source: Chemical Rubber Co. [44]

Other studies have also rated the overall health effects arising from methanol use and place methanol as a higher risk than diesel but less than gasoline, e.g., DOE Report, DOE/CE/50179-1 (referred to in ref. 35).

4.2/ Global Impacts

4.2.1/ Effects on Air Quality

It is assumed that the only engines allowed in operation in new buses will be ones that meet the new standards. Each alternative fuel strategy has one or more emission that is hardest to control. When these emissions are reduced, the margin by which the other emissions are lower than their limits constitutes a bonus and the major consequence of adopting one strategy over another. The following table lists the hardest-to-meet emission(s) and the resultant emission bonuses.

Table 32/ Exhaust Emission Trade-offs

	Diesel	Gasoline	Methanol	Propane	CNG
Limiting Emission	Particulates/ NOx	HC/NOx	Methanol/ Aldehydes	HC*/NOx Aldehydes	HC*/NOx
Benefits	Low CO	Low PM	Low PM	Low PM	Low CO/PM

* Low if propane and methane not counted as pollutants

The major impact resulting from the choice of any of the alternative fuels will be the lowering of particulate emissions. Methanol, propane, and CNG are hydrogen rich and do not form soot. The remaining low level of particulates from engines using these fuels is believed to arise almost entirely from the inadvertent combustion of engine oil and not from the fuel itself. As such, the values observed depend greatly on the engine design. In the case of the DDA two-stroke engines converted to methanol, the source of the oil is supposed to be due to accumulation in the air box in the vicinity of the inlet ports. With the various engines converted to gaseous fuels using spark ignition, the increased suction due to throttling can cause oil intrusion even though steps are taken to block obvious sites, e.g., by fitting valve stem oil seals where they are normally absent. Continued design refinements can be expected to reduce particulates from these sources to negligible levels.

The alternative fuels strategy, however, may cause inadvertent increase in some emissions relevant to the diesel. Carbon monoxide emissions with the diesel are extremely low due to its very lean operation. Conversion to gaseous fuels involves Otto cycle operation with intake throttling and calibration nearer to the stoichiometric point. With natural gas, at least, operation is possible at air-fuel ratios in the region of 25:1 and the engine under development in the MTO supported project (Cummins L10) shows CO values less than that reported for equivalent diesels. On the other hand, the only propane engine test data available directly comparable with the diesel engine show increased CO. The methanol 6V-71 is partly throttled and higher CO emissions than for the diesel have been reported (Table 7). Low values were reported by the manufacturer for DDA 6V-92 engines (unthrottled) on methanol but in-use engines re-examined by an

independent agency showed greatly increased CO levels. Evaluation is greatly complicated by the variation of test cycles used and the shortage of tests conducted under the new EPA transient cycle, under which the 1989 and 1994 standards will have to be met. As all the alternative fuelled engines are prototypes, improvements are to be expected and CO is easy to remove with oxidation catalysts. The best estimate suggests that the implementation of the alternative fuels will be neutral with respect to CO.

In the analysis of engine exhaust, the value reported as hydrocarbons includes all compounds responding to the flame ionization detector (FID) that is used. One component arises from unburnt fuel and the other is a mixture of unoxidized or partly oxidized reaction products of combustion. The levels of reported hydrocarbons can be significant with the alternative fuels. With natural gas, the dominant methane component is unreactive, either locally as a toxic agent or globally as an agent involved in the photochemical generation of other atmospheric toxics, e.g., ozone. Because of this, the methane component may be exempted from the restriction on hydrocarbon emissions and the higher HC levels arising from lean calibration permissible with natural gas may be acceptable.

Unburnt propane emissions from propane engines will be counted as hydrocarbons but with stoichiometric operation they will not be excessive. One advantage both fuels have is that the unoxidized reaction products, included in the HC figure, are low in direct toxic effect compared with those from diesel combustion which consists partly of polynuclear aromatics with pronounced mutagenic and carcinogenic activity. With methanol engines the FID-responding component is frequently reported as two separate fractions – unburnt methanol and the non-methanol fraction. The latter consist of various combustion products including formaldehyde, higher oxygenates, and hydrocarbons. While this fraction may be very low, the methanol level itself may be quite high, particularly in diesel cycle engines where firing becomes uncertain during light loads and low temperatures. Both methanol and formaldehyde are easy to oxidize with exhaust catalysts. However, while the catalyst is passing through an intermediate temperature range during warming up, formaldehyde can be formed from methanol at a greater rate than it is itself oxidized. This could be significant when vehicles are warmed up or idled for prolonged periods under cold ambient conditions which normal engine test procedures do not allow for. At present there is insufficient information to judge whether in practice there will be a problem in actual bus operation. On a larger scale, formaldehyde does play a part in smog formation and the generation of ozone though its lifetime in the atmosphere is short. Methanol is considered to be much less reactive photochemically [45] and one of the strategies adopted by EPA and California in the reduction of urban ozone involves the substitution of gasoline with methanol or other oxygenates.

Nitrogen oxides are a problem emission with both diesel and gaseous fuels. In the latter case this is due to their inherent higher combustion temperatures. The standards will be met either by using the feedback control/three-way catalyst systems now used for gasoline engines or, in the case of natural gas, by operating at an extreme lean calibration where the NO_x generation rate is lower. Methanol offers a distinct benefit in lowering levels well below the standard and will therefore be a useful adjunct to efforts to control global acid emissions (acid rain).

4.2.2/ Surface Environmental Effects

The gaseous fuels are quickly dispersed in the open and, apart from an immediate fire hazard, pose no health problem if released accidentally in large quantities. The liquid fuels, on the other hand, are subject to the risk of accidental spillage during bulk transportation and consequent environmental effects. Methanol is soluble in water and easily dispersed. Though poisonous to higher forms of life including man, in dilute form (below 1%) it is tolerated by most aquatic organisms. It is capable of being metabolized by micro-organisms and its residence time in aquatic environments is measured in hours. Spills on dry land are also rapidly metabolized by bacteria and moulds with restoration of normal soil properties after a few weeks [35]. By comparison diesel fuel is insoluble, non-volatile, and also lighter than water. A recent spill from a bulk barge in a river in the Pittsburgh area closed down commercial activity for several days. The non-miscibility means that the hazard can be transported for many miles downstream with respect to fire, poisoning of aquatic life, and contamination of water supplies to populated areas. The aromatic components particularly are carcinogenic in the ppm range. Diesel fuel and its poisonous effects persist in the soil indefinitely.

4.3/ Relative Environmental Impact of Buses

Although common standards will be met by all alternatives, there will be differences in the amounts of regulated pollutants emitted between the options considered. To estimate the relative environmental impact of buses, the pollutants generated by buses, cars, and trucks in a typical city, such as Toronto, were estimated. The pollution generated by the buses as a percentage of the total generated by cars and trucks was used as a measure of relative impact. Data obtained from the Transportation Tomorrow Survey [46] for daily trips and trip length were used to estimate the total kilometres driven each day by cars. Data for trucks were obtained from the Toronto Goods Movement Study [47].

In comparing the relative environmental impact of buses with different forms of propulsion, the diesel, propane, natural gas, and methanol buses are the most similar, and the most easily compared, because their emissions occur at the point of use and are expressed in similar terms (g/bhp-hr or g/mi). To bring trolley buses into the comparison requires some discussion as to how the comparison is to be done. Clearly, the electric trolleys have no significant emission of any pollutant at the point of use. However, they do produce pollutants and hazardous waste at fossil and nuclear powered generating stations respectively. Over and above the pollutants produced by alternative fuelled buses, fossil fuel generating stations produce sulphur dioxide and fly ash. The amount produced depends on the type and quality of the fuel. In Ontario, the fuel source for generating electricity is nuclear 50%, hydraulic 25%, and fossil 25%.

While nuclear and hydraulic stations meet most of the base load demand of the province, coal and oil burning stations provide the bulk of the electricity required during peak demand periods. The electricity consumed by public transit vehicles constitutes largely

a peak demand, which is at present primarily met by coal burning powerplants. Therefore, it is reasonable to assume that the electricity consumed by trolley buses is mostly produced by coal powered generators, the emissions of which are documented in a 1989 Ontario Hydro Report [48]. This may change in the longer term, as the electricity-generating mix in Ontario is changed, and depending on which generating source (nuclear or fossil) is displaced by new fuel types.

In order to assess the relative magnitude of air pollution caused by trolley buses, the Ontario Hydro data were used to infer the atmospheric emissions associated with each mile of trolley service. In this process, the energy efficiency of the trolley was assigned the 2.92 kWh/km figure used in the rest of the report. Furthermore, all energy losses including transformation, rectification, and transmission of electricity from the generating station to the trolley bus were assumed to be 10%. For comparative purposes, data for diesel, propane, natural gas, and methanol powered buses were also considered. The exhaust emissions of diesel buses were quantified recently by Environment Canada [49] employing new 1989 MCI (Motor Coach Industries) buses and in-use 1982 diesel buses. These results, as measured accurately on the Environment Canada heavy-duty chassis dynamometer are summarized in Table 33. The exhaust emissions of natural gas, methanol, and clean diesel buses were inferred from the engine dynamometer test data provided by the Cummins Engine Co. [50] and Detroit Diesel Co. [14], respectively. Propane powered buses are not included in this comparison, since up-to-date emission data are not available for this option.

Table 33/ Comparison of the Air Pollution Associated with Buses

Bus Type	NOx (g/ml)	HC (g/ml)	PM (g/ml)	SO ₂ (g/ml)	CO (g/ml)
1982 Diesel	34.1	3.7	1.7	minimal	17.0
1989 Diesel	18.1	2.0	1.9	minimal	3.0
Natural Gas	13.8	2.5	0.3	minimal	0.5
Methanol	7.3	1.0	0.3	minimal	7.8
Trolley	13.6	minimal	1.4	42.9	minimal

Trolleys were considered for transit use in the 1960s and 1970s to eliminate the pollutants and soot generated by the use of diesels. However, modern diesels and alternative fuelled buses, which have to meet the standards listed in Table 1, have significantly lower emission levels, which is borne out by the estimates provided in Table 33. Consequently, the environmental benefits of introducing trolleys today are not as great as in the past. However, all of the alternative fuelled buses, including trolleys, overcome two of the most troublesome and noticeable effects of the diesel bus, namely smoke and odour.

It is difficult to directly compare the impacts of the emissions produced at the generating station with that produced by the bus locally. However, an indication of the relative magnitudes of emissions from various transportation sources can be obtained by comparing the daily kilometres travelled each day by buses, cars, and trucks. Taking

Toronto as an example, daily travel in Toronto is approximately 360 000 km by buses, 38 500 000 km by cars, and about 8 600 000 km by trucks. Of the total NO_x and volatile organic compounds (VOCs) produced by road transportation, buses would account for approximately 2.7% and 0.6% respectively. Modern diesels and alternative fuelled buses would reduce the NO_x contribution to approximately 1.5%. Hence, the contribution to NO_x and VOC levels caused by buses locally, in the urban area, are on the order of 1.5% and 0.6% respectively, almost regardless of the propulsion type used. That is, the levels for diesel buses will be near these values, the levels for propane, natural gas, or methanol will be somewhat lower, the levels for trolley buses lower still, at zero. The contribution of bus emissions, relative to total transportation emissions, is simply very small. As noted above, all the alternatives to diesel avoid the smoke and odour associated with the conventional diesel. Further, the proportion of buses in a fleet for which the locally cleanest alternative, trolleys, may be regarded as feasible is typically 5 to 10% (currently 6% in Toronto). If these buses are diesel or one of the other alternatives rather than trolleys, the urban NO_x and VOC levels would increase by 0.09% and 0.04% respectively, even assuming that no emissions whatsoever are produced at the electrical generating stations.

When these emissions are included (see Table 33), the differences between trolley buses and other buses become negligible, except that fossil fuel burning electrical generating stations produce significant amounts of sulphur dioxide.

Recently, the issue of global warming has been added to the list of environmental concerns. The principal atmospheric gases involved in global warming are carbon dioxide (CO₂), methane (CH₄), CFC-11, CFC-12, and nitrous oxide (N₂O). The combustion of fuel in engines results in the emission of CO₂, water vapour, and trace amounts of other gases.

Some of the ways being considered to reduce the production of CO₂ from engines are to increase engine efficiency, reduce demand, and conserve and switch fuels. The concept behind fuel switching is to burn fuels with higher hydrogen-to-carbon ratios in engines because they produce less CO₂ per unit of energy input. However, for completeness, one must also consider the CO₂ created in the production and delivery of the fuel. Recently, two studies of the "cradle-to-grave" emission of CO₂ have been undertaken by scientists at University of California, Davis and General Motors [51, 52]. The former shows that the use of methanol or electricity derived from coal results in an additional 50% and 25% respectively of CO₂ produced over a petroleum powered car. The use of natural gas in a car directly or when burned at a power generating station results in the production of approximately 19% less CO₂ than produced in a petroleum based car. The General Motors study shows similar results. It shows that natural gas produces 19% less CO₂ than gasoline powered vehicles and 8% less than diesel. Again, methanol made from coal appears to be approximately 70% worse than gasoline. However, methanol made from natural gas can be from 0-9% better than gasoline.

5/ ECONOMIC COMPARISON

The full-scale adoption of alternative propulsion options will have wide ranging economic ramifications, which cannot be fully quantified until significant experience has been gained with each alternative, especially with the newer alternatives. In this section, we have attempted to integrate the best knowledge available on the subject to arrive at some tentative predictions.

The alternatives considered in this section are:

- 1989 Diesel Bus (Baseline case)
- Future Diesel Bus (Clean diesel)
- Propane Bus
- Natural Gas Bus
- Methanol Bus
- Electric Trolley

The economic comparison of these alternatives is assessed here by a life-cycle cost analysis of each option relative to that of the 1989 diesel bus at a common operational, environmental, and safety standard. The operational standard is set by the present diesel experience. The environmental standard is dictated by the EPA bus exhaust emission standards as adopted by the U.S. Clean Air Act Amendment of 1990. The safety standards are not by a combination of regulatory requirements and present transit industry norms in Ontario.

The most significant cost items specific to each option are:

- Fuel or energy price
- Bus capital cost
- Fuelling equipment cost
- Garage modification cost
- Bus maintenance and inspection cost
- Fuelling equipment maintenance cost
- Garage maintenance cost

Common cost items such as bus drivers' salaries and administrative expenses were not dealt with in this comparative study. Incremental costs, viz. costs for a specific option relative to the corresponding costs for the baseline, were identified as the pertinent measure of comparison.

The fuel and energy prices are summarized in Table 34.

Table 34/ Fuel and Energy Prices

1989 Diesel	\$37.0 / 100 L
Future Diesel	\$46.0 / 100 L
Propane	\$20.3 / 100 L
Compressed Natural Gas	\$13.5 / 100 m ³
Methanol	\$16.7 / 100 L
Electricity	\$ 6.6 / 100 kW-h

Notes: Diesel price includes provincial sales tax of \$10.9 / 100 L.

Propane price includes provincial sales tax of \$4.3 / 100 L.

No provincial sales tax for CNG, propane and electricity.

The price of natural gas is set by long-term contracts between large users and suppliers. The present price paid by TTC is 12 ¢/m³, which is the basis for our assumption. A further 1.5 ¢/m³ is added to this price to account for the average energy cost of compression to produce compressed natural gas.

The price of propane for large-scale users with long-term contracts is running at approximately 20.3 ¢/L in Ontario (as of June 1990). This price includes a provincial sales tax of 4.3 ¢/L.

The price of electricity for the largest trolley bus operator in Ontario, TTC, is currently 6.6 ¢/kW-h.

Methanol is used primarily as a chemical feedstock rather than an automotive fuel. Therefore, the future price of fuel-grade methanol has to be estimated. Industry and government sponsored reports, which have analyzed the production cost of methanol from natural gas in various parts of the world, conclude that the price of fuel-grade methanol would be in the 14 to 21 ¢/L range. The price adopted in this report is 16.7 ¢/L.

The fuel- and energy-efficiency of buses is another crucial parameter influencing the fuelling cost of each alternative. The diesel and trolley bus efficiencies are well established, while those of the alternative fuels are derived from the demonstration data accumulated in Ontario and other jurisdictions. These are summarized in Table 35.

Table 35/ Fuel Efficiency and Fuel Cost

	Fuel Efficiency	Fuel Cost
1989 Diesel Bus	53.7 L / 100 km	\$19.9 / 100 km
Future Diesel Bus	59.4 L / 100 km	\$27.3 / 100 km
Propane Bus	96.5 L / 100 km	\$19.6 / 100 km
Natural Gas Bus	67.3 m ³ / 100 km	\$ 9.1 / 100 km
Methanol Bus	140 L / 100 km	\$23.4 / 100 km
Electric Trolley	292 kWh / 100 km	\$19.3 / 100 km

The integration of fuel prices and fuel efficiency produces final fuel costs for each option expressed as the cost of the fuel necessary to cover 100 km.

The price of the baseline 1989 diesel bus is \$186,000, a number that represents the average price paid by Ontario transit systems in 1989. The \$202,000 price of the 1991 diesel is an estimate, which includes the cost of the particulate trap and an upgraded diesel engine. The prices for the natural gas, methanol, and propane buses were estimated by accounting for the inherent cost of the new engines and fuel storage systems. The resulting prices are \$200,000 for the methanol and propane buses and \$220,000 for the natural gas bus. It should be noted that some prototype alternative fuel buses have been purchased at higher prices, which reflect the relatively high development costs. The \$427,000 electric trolley bus price was established in an independent consultant's report, which included a survey of most recent North American purchases. At present, the alternative fuel buses, including the electric trolley, are exempted from the 8% provincial sales tax. This fact has been accounted for in establishing the prices provided in Table 36.

Table 36/ Bus Capital Costs

1989 Diesel Bus	\$186,000
Future Diesel Bus	\$202,000
Propane Bus	\$200,000
Natural Gas Bus	\$220,000
Methanol Bus	\$200,000
Electric Trolley	\$427,000*

* Based on Cole Sherman report

The additional or incremental infrastructure costs, viz., costs that have to be incurred above and beyond those incurred by typical diesel fleets, are significant for some of the alternatives. Natural gas, methanol, and propane necessitate the installation of new fuelling stations and improvements to the garaging facilities to mitigate the hazards of dealing with more volatile fuels. In the estimation of these costs, a typical garage handling 250 transit buses has been considered.

The fuelling station costs on a per-bus basis are \$24 K for natural gas, \$4 K for methanol, and \$2 K for propane. These figures are based on the recent experience gained in Ontario and other North American jurisdictions. With indoor bus storage, the cost of garage improvements is estimated at \$4 K per bus for methanol, natural gas, and propane. This estimate represents the incremental cost of building a new garage to accommodate alternative fuel buses. The introduction of new electric trolley lines necessitates a new overhead system and transformer substations. The installation cost of these is estimated by TTC at \$1.53 M per two-way route kilometre. The present practice in Toronto and Hamilton results in 1.7 buses being allocated per two-way route kilometre. This figure includes 10-12% spare units. Thus, the overhead system cost on a per bus basis amounts to approximately \$926 K. However, this and most other infrastructure

elements have a longer useful life than the bus itself. This fact is recognized in our economic analysis by assigning an appropriate residual value to the incremental infrastructure costs at the end of the bus life.

Table 37/ Infrastructure Capital Costs Per Bus

	Fuelling Equipment	Garage Modifications
Diesel	\$2,000	\$0
Propane	\$2,000	\$4,000
Natural Gas	\$24,000	\$4,000
Methanol	\$4,000	\$4,000
Electricity	\$926,000* (\$463,000 residual value)	\$0

* New overhead system capital cost of \$1.53 M per two-way route km. Average headway between trolleys is 1.21 km in the Canadian systems of Toronto, Hamilton, Vancouver, and Edmonton. Therefore, new two-way overhead system cost per trolley amounts to $\$1.53 \text{ M} \times (1.21 / 2) = \$0.926 \text{ M}$.

The incremental bus and infrastructure maintenance costs of all options are quantified in this report as well. However, these are only estimates that attempt to predict inherent differences, rather than those experienced at present with prototype units. These estimates are provided in the appendix of this report.

The above facts and figures are integrated in a life-cycle cost analysis model, which was developed at MTO for this specific project. The analysis sums up all incremental costs in 1990 dollars relative to those of the 1989 diesel bus over an 18-year life cycle. During this period, a typical Ontario transit bus runs 1.2 million service kilometres. In its earlier years the bus is used more extensively than in its later years. This fact is incorporated into the life-cycle cost analysis program. All costs are brought to their present values by employing a discount rate of 5%, which represents the net effect of interest rates and inflation.

Figure 25 represents the results of the analysis for the baseline case where the present taxation policy is adopted. The horizontal line at zero incremental unit represents the 1989 diesel case, and the individual bars quantify the individual incremental cost in dollars per 100 km for each option. For the trolley two bars are displayed. These represent the extremes of a trolley application where no overhead system capital expenditure is incurred and that of an entirely new application. In locations where an existing trolley overhead system has to be refurbished, incremental costs between these two extremes would apply.

The most obvious conclusion suggested by this figure is that all alternatives except the natural gas will result in higher life-cycle costs. The trolley is by far the most costly alternative.

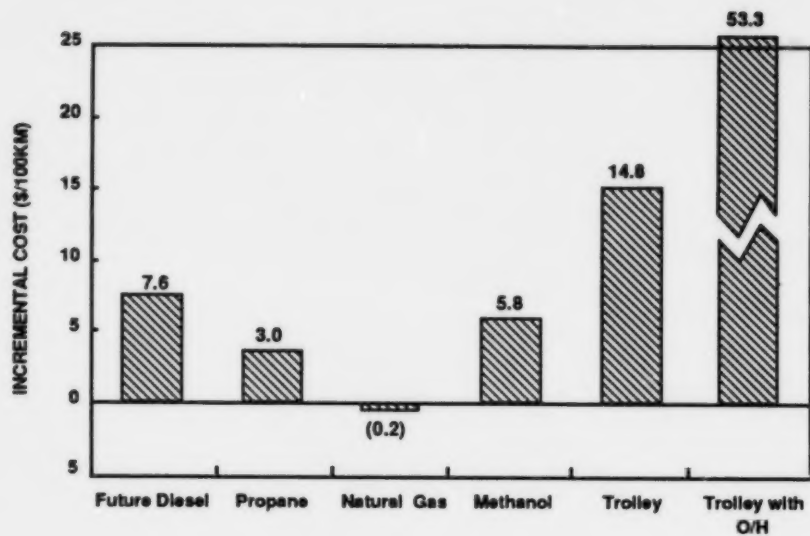


Figure 25/ Life-Cycle Cost Increment – Relative to 1989 Diesel

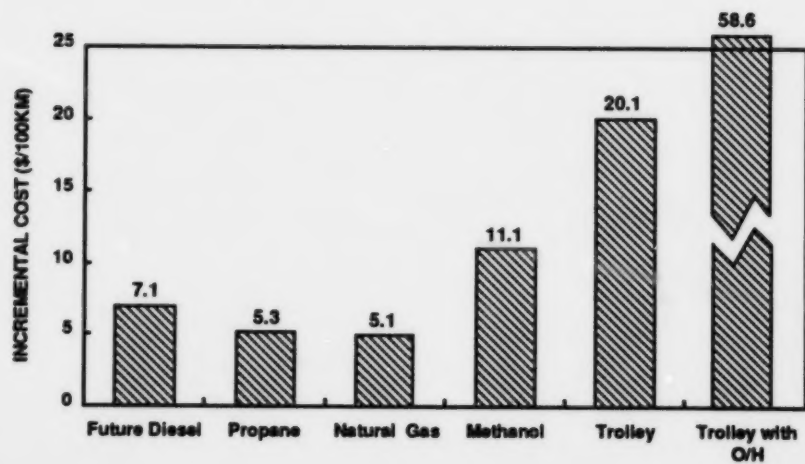


Figure 26/ Life-Cycle Cost Increment – Relative to 1989 Diesel
(All Provincial Taxes Off)

A second analysis was performed by removing the provincial sales tax (PST) for the diesel fuel and diesel bus. This provides a comparison, in which the PST is not a factor in the life-cycle cost of any alternative. The resulting incremental costs are displayed in Figure 26. Here, we see all alternatives resulting in higher costs. It is worth noting, however, that the 1989 diesel is not a credible or even legally acceptable alternative for the future. The future diesel is the true baseline for the period beyond 1991. All alternatives have to compete against this new baseline. This perspective is represented quantitatively in Figure 27, which points to the conclusion that while natural gas, propane, and methanol options may compete well with the future diesel, the trolley is at a significant economic disadvantage.

The sensitivity of these conclusions to the fuel price was tested by varying fuel prices in 10% increments with respect to present prices. This sensitivity analysis can also be used to estimate the effect of a 10% improvement in fuel consumption, obtained from improved engines or regeneration in the case of trolleys. Figure 28 provides a summary of this analysis. The primary conclusion of this analysis is that the trends predicted with present prices are essentially unaffected by up to 20% price variations.

The sensitivity of the life-cycle cost of trolley buses to overhead system utilization and overhead system cost was also assessed. To this end, the average overhead distance per trolley was varied between 1.21 km (present practice) and 500 metres (shortest conceivable distance).

In the most optimistic scenario – trolley spacing of 500 m, as discussed on page 65 – the overhead cost per bus is reduced to \$382,500. This reduces the incremental life-cycle cost of the trolley to \$29.0/100 km (compare with Figure 25). Clearly, this is a major cost reduction; however, it may not be attainable on most transit routes.

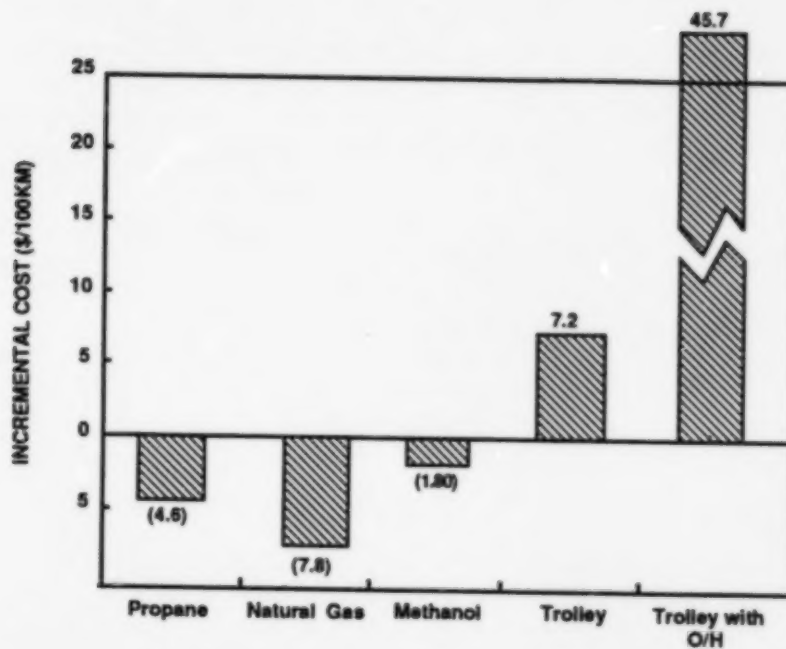


Figure 27/ Life-Cycle Cost Increment – Relative to Future Diesel

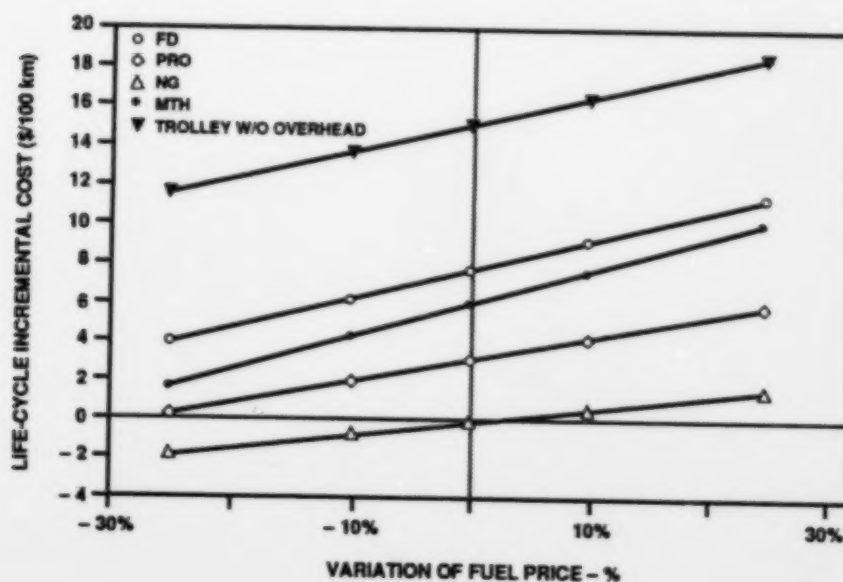


Figure 28/ Sensitivity Analysis – Relative to Baseline Fuel Cost

6/ CONCLUSIONS

- 1/ Natural gas, methanol, propane, and clean diesel offer the potential to meet the environmental challenges of the 1990s. However, each of these alternatives will require more in-service evaluation to completely assess its characteristics against the traditional diesel bus. Trolleys can also meet the environmental challenges, provided the electricity is derived from non-polluting energy sources.
- 2/ The alternative fuel demonstrations in Ontario and elsewhere are the only major contributors to the development and evaluation process, which may help to establish objectively the operational and cost parameters of the alternative fuels. These efforts should be continued.
- 3/ The life-cycle cost analysis presented in this report draws upon the best technical and economic data available in North America. The tentative conclusions of this analysis are that, among the six alternatives considered, natural gas has the smallest life-cycle cost and the electric trolley the largest in medium to large transit systems. Technological developments are not expected to change this conclusion.
- 4/ The development and introduction of alternative fuelled buses and modern clean diesel buses offer significant reductions in pollutants and soot and are capable of meeting the stricter 1991 and 1993 emission standards. From an overall perspective of energy security, environmental impact, economy, and operational flexibility, these buses should be considered when planning any bus route. Trolleys do not emit pollutants at the point of use, and hence will also meet the stricter 1991 and 1993 emission standards. However, peak period trolley service does lead to the generation of pollutants and hazardous waste materials at power plant sites. The environmental benefits of introducing trolleys rather than modern diesels or alternative fuelled buses are not as great today as in the past. In a typical modern city where trolleys account for 5-7% of the bus fleet, the effect on the environment from using alternative fuelled buses rather than trolleys is approximately 0.09% more NO_x and 0.04% more VOCs.

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APPENDIX

PROPULSION OPTIONS FOR TRANSIT BUSES IN ONTARIO

31582B.WK1

LIFE-CYCLE COST ANALYSIS

CURRENT TAX LEVELS

Written: September 12, 1990

Updated: January 14, 1991

ANALYSIS IS BASED ON FOLLOWING ASSUMPTIONS:

	FUEL PRICE		
	BASE	TAX	TOTAL
1989 Diesel	\$26.1 /100 litres	\$10.9 /100 litres	\$37.0 /100 litres
Low Sulphur Diesel	\$29.1 /100 litres	\$10.9 /100 litres	\$40.0 /100 litres
Reformulated Diesel	\$35.1 /100 litres	\$10.9 /100 litres	\$46.0 /100 litres
Propane	\$16.0 /100 litres	\$4.3 /100 litres	\$20.3 /100 litres
Compressed NG	\$13.5 /100 cubic metres	\$0.0 /100 cubic metres	\$13.5 /100 cu.m
Methanol	\$16.7 /100 litres	\$0.0 /100 litres	\$16.7 /100 litres
Electricity	\$6.6 /100 kW.h	\$0.0 /100 kW.h	\$6.6 /100 kW.h

	Annual Veh. Maint	Engine/ Motor Rebuild	Trap/ Catalyst Replace	Bus Capital Cost	Bus Residual Cost (PV)
1989 Diesel	\$23,000	\$10,000	\$0	\$186,000	\$500
1991 Diesel	\$23,750	\$10,000	\$3,000	\$202,000	\$500
Propane	\$24,500	\$10,000	\$1,000	\$200,000	\$500
Natural Gas	\$24,500	\$10,000	\$1,000	\$220,000	\$500
Methanol	\$24,500	\$10,000	\$1,000	\$200,000	\$500
Electricity	\$23,000	\$1,600	\$0	\$427,000	\$125,000

	-----FUEL ECONOMY-----		-ENGINE LIFE-	
1989 Diesel	53.7 L/100km =	5.25 mpg	400,000 km's	
1991 Diesel	59.4 L/100km =	4.75 mpg	400,000 km's	
Propane	96.5 L/100km =	2.92 mpg	400,000 km's	
Natural Gas	67.3 cm/100km	0.0261 mi/cf	400,000 km's	
Methanol	140 L/100km =	2.02 mpg	400,000 km's	
Electricity	292 kWh/100k	0.213 mi/kWh	128,000 km's	

	INFRASTRUCTURE COSTS (PER BUS)						
	Capital		Residual		Annual Maintenance		Periodic
Propulsion	Fuel Eqp	Gar Mod	Fuel Eqp	Gar Mod	Fuel Eqpt	Garage	Inspection
1989 Diesel	\$0	\$0	\$0	\$0	\$23	\$0	\$0
1991 Diesel	\$0	\$0	\$0	\$0	\$23	\$0	\$0
Propane	\$2,000	\$4,000	\$0	\$0	\$23	\$100	\$0
Natural Gas	\$24,000	\$4,000	\$0	\$0	\$500	\$100	\$1,000 every 3 years - aluminum vehicle tanks
Methanol	\$4,000	\$4,000	\$0	\$0	\$23	\$100	\$0
Electricity	\$925,650	\$0	\$462,825	\$0	\$6,000	\$0	\$0

Discount Rate= 5.0% Number of Buses 250

CASE I - 1989 Diesel Baseline

Year	Annual km	Cumulative km	Annual Bus Maint	PV Annual Bus Maint	Annual Fuel Bill	PV Annual Fuel Bill	Periodic Engine Rebuild	PV Engine Rebuild	Annual Operating Cost	Current Value of Opr Cost	Cumulative Operating Cost	Year
1	100,000	100,000	\$5,750	\$5,476	\$19,869	\$18,923	\$0	\$0	\$25,619	\$24,399	\$24,399	1
2	100,000	200,000	\$11,500	\$10,431	\$19,869	\$18,022	\$0	\$0	\$31,369	\$28,452	\$52,851	2
3	100,000	300,000	\$17,250	\$14,901	\$19,869	\$17,163	\$0	\$0	\$37,119	\$32,065	\$84,916	3
4	95,000	395,000	\$23,000	\$18,922	\$18,875	\$15,529	\$0	\$0	\$41,875	\$34,451	\$119,367	4
5	90,000	485,000	\$23,000	\$18,021	\$17,882	\$14,011	\$10,000	\$7,835	\$50,882	\$39,867	\$159,234	5
6	85,000	570,000	\$23,000	\$17,163	\$16,889	\$12,602	\$0	\$0	\$39,889	\$29,765	\$189,000	6
7	80,000	650,000	\$23,000	\$16,346	\$15,895	\$11,296	\$0	\$0	\$38,895	\$27,642	\$216,642	7
8	75,000	725,000	\$23,000	\$15,567	\$14,902	\$10,086	\$0	\$0	\$37,902	\$25,653	\$242,295	8
9	70,000	795,000	\$23,000	\$14,826	\$13,908	\$8,965	\$0	\$0	\$36,908	\$23,791	\$266,086	9
10	65,000	860,000	\$23,000	\$14,120	\$12,915	\$7,929	\$10,000	\$6,139	\$45,915	\$28,188	\$294,274	10
11	60,000	920,000	\$23,000	\$13,448	\$11,921	\$6,970	\$0	\$0	\$34,921	\$20,418	\$314,692	11
12	55,000	975,000	\$23,000	\$12,807	\$10,928	\$6,085	\$0	\$0	\$33,928	\$18,892	\$333,584	12
13	50,000	1,025,000	\$23,000	\$12,197	\$9,934	\$5,268	\$0	\$0	\$32,934	\$17,466	\$351,050	13
14	45,000	1,070,000	\$23,000	\$11,617	\$8,941	\$4,516	\$0	\$0	\$31,941	\$16,132	\$367,182	14
15	40,000	1,110,000	\$23,000	\$11,063	\$7,948	\$3,823	\$0	\$0	\$30,948	\$14,886	\$382,069	15
16	35,000	1,145,000	\$23,000	\$10,537	\$6,954	\$3,186	\$0	\$0	\$29,954	\$13,722	\$395,791	16
17	30,000	1,175,000	\$23,000	\$10,035	\$5,961	\$2,601	\$0	\$0	\$28,961	\$12,635	\$408,426	17
18	25,000	1,200,000	\$23,000	\$9,557	\$4,967	\$2,064	\$0	\$0	\$27,967	\$11,621	\$420,047	18
January 14, 1991				\$237,034		\$169,039		\$13,974	Capital Cost=	\$186,000		
									Residual Value=	\$500		
									Total Life-cycle Cost=	\$605,547		

CASE II - 1991 Low Sulphur Diesel

Year	Annual km	Cumulative km	Annual Bus Maint	PV Annual Bus Maint	Bus Maint Increm	PV Bus Maint Increm	Annual Fuel Bill	PV Annual Fuel Bill	Fuel Bill Increm	PV Fuel Bill Increm	Annual Overhead Increm	PV Annual Overhead Increm
1	100,000	100,000	\$5,938	\$5,655	\$188	\$179	\$23,760	\$22,628	\$3,891	\$3,706	\$0	\$0
2	100,000	200,000	\$11,875	\$10,771	\$375	\$340	\$23,760	\$21,551	\$3,891	\$3,529	\$0	\$0
3	100,000	300,000	\$17,813	\$15,387	\$563	\$486	\$23,760	\$20,525	\$3,891	\$3,361	\$0	\$0
4	95,000	395,000	\$23,750	\$19,539	\$750	\$617	\$22,572	\$18,570	\$3,696	\$3,041	\$0	\$0
5	90,000	485,000	\$23,750	\$18,609	\$750	\$588	\$21,384	\$16,755	\$3,502	\$2,744	\$0	\$0
6	85,000	570,000	\$23,750	\$17,723	\$750	\$560	\$20,196	\$15,070	\$3,307	\$2,468	\$0	\$0
7	80,000	650,000	\$23,750	\$16,879	\$750	\$533	\$19,008	\$13,509	\$3,113	\$2,212	\$0	\$0
8	75,000	725,000	\$23,750	\$16,075	\$750	\$508	\$17,820	\$12,061	\$2,918	\$1,975	\$0	\$0
9	70,000	795,000	\$23,750	\$15,309	\$750	\$483	\$16,632	\$10,721	\$2,724	\$1,756	\$0	\$0
10	65,000	860,000	\$23,750	\$14,580	\$750	\$460	\$15,444	\$9,481	\$2,529	\$1,553	\$0	\$0
11	60,000	920,000	\$23,750	\$13,886	\$750	\$439	\$14,256	\$8,335	\$2,335	\$1,365	\$0	\$0
12	55,000	975,000	\$23,750	\$13,225	\$750	\$418	\$13,068	\$7,277	\$2,140	\$1,192	\$0	\$0
13	50,000	1,025,000	\$23,750	\$12,595	\$750	\$398	\$11,880	\$6,300	\$1,945	\$1,032	\$0	\$0
14	45,000	1,070,000	\$23,750	\$11,995	\$750	\$379	\$10,692	\$5,400	\$1,751	\$884	\$0	\$0
15	40,000	1,110,000	\$23,750	\$11,424	\$750	\$361	\$9,504	\$4,572	\$1,556	\$749	\$0	\$0
16	35,000	1,145,000	\$23,750	\$10,880	\$750	\$344	\$8,316	\$3,810	\$1,362	\$624	\$0	\$0
17	30,000	1,175,000	\$23,750	\$10,362	\$750	\$327	\$7,128	\$3,110	\$1,167	\$509	\$0	\$0
18	25,000	1,200,000	\$23,750	\$9,869	\$750	\$312	\$5,940	\$2,468	\$973	\$404	\$0	\$0
			\$244,763			\$7,729		\$202,142		\$33,103		\$0

-----Periodic Costs-----

Year	Engine Rebuild	Trap Replace	Conv'n Cost	Sum of Periodic	PV Sum of Periodic	Sum of Periodic Increm	PV SoP Increm	Annual Operat'g Cost	PV Operating Cost	Cumulative Operating Cost	Operating Cost Increm	PV Opr Cost Increm
1	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,697	\$28,283	\$28,283	\$4,078	\$3,884
2	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$35,635	\$32,322	\$60,605	\$4,266	\$3,869
3	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$41,572	\$35,912	\$96,517	\$4,453	\$3,847
4	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$46,322	\$38,109	\$134,626	\$4,446	\$3,858
5	\$10,000	\$3,000	\$0	\$13,000	\$10,186	\$3,000	\$2,351	\$58,134	\$45,549	\$180,175	\$7,252	\$5,682
6	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$43,946	\$32,793	\$212,968	\$4,057	\$3,028
7	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$42,758	\$30,387	\$243,355	\$3,863	\$2,745
8	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$41,570	\$28,136	\$271,492	\$3,668	\$2,483
9	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$40,382	\$26,031	\$297,522	\$3,474	\$2,239
10	\$10,000	\$3,000	\$0	\$13,000	\$7,981	\$3,000	\$1,842	\$52,194	\$32,043	\$329,565	\$6,279	\$3,855
11	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$38,006	\$22,221	\$351,786	\$3,085	\$1,803
12	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$36,818	\$20,502	\$372,287	\$2,890	\$1,609
13	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$35,630	\$18,895	\$391,183	\$2,695	\$1,429
14	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$34,442	\$17,396	\$408,578	\$2,501	\$1,263
15	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$33,254	\$15,996	\$424,574	\$2,306	\$1,109
16	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$32,066	\$14,690	\$439,264	\$2,112	\$967
17	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$30,878	\$13,472	\$452,736	\$1,917	\$837
18	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,690	\$12,337	\$465,072	\$1,723	\$716
				\$18,167			\$4,192					

Facility Capital Cost=
Facility Residual Value=

Capital Cost=
Residual Value=
Life-cycle Cost=
Net Incr=
\$45,025

January 14, 1991

CASE III -1991 Reformulated Diesel

Year			PV		PV		PV		PV		PV	
	Annual km	Cumulative km	Annual Bus Maint	Annual Bus Maint	Bus Maint Incr	Bus Maint Incr	Annual Fuel Bill	Annual Fuel Bill	Fuel Bill Incr	Fuel Bill Incr	Annual Overhead Incr	Annual Overhead Incr
1	100,000	100,000	\$5,938	\$5,655	\$188	\$179	\$27,324	\$26,023	\$7,455	\$7,100	\$0	\$0
2	100,000	200,000	\$11,875	\$10,771	\$375	\$340	\$27,324	\$24,783	\$7,455	\$6,762	\$0	\$0
3	100,000	300,000	\$17,813	\$15,387	\$563	\$486	\$27,324	\$23,603	\$7,455	\$6,440	\$0	\$0
4	95,000	395,000	\$23,750	\$19,539	\$750	\$617	\$25,958	\$21,355	\$7,082	\$5,827	\$0	\$0
5	90,000	485,000	\$23,750	\$18,609	\$750	\$588	\$24,591	\$19,268	\$6,709	\$5,257	\$0	\$0
6	85,000	570,000	\$23,750	\$17,723	\$750	\$560	\$23,225	\$17,331	\$6,337	\$4,729	\$0	\$0
7	80,000	650,000	\$23,750	\$16,879	\$750	\$533	\$21,859	\$15,535	\$5,964	\$4,238	\$0	\$0
8	75,000	725,000	\$23,750	\$16,075	\$750	\$508	\$20,493	\$13,870	\$5,591	\$3,784	\$0	\$0
9	70,000	795,000	\$23,750	\$15,309	\$750	\$483	\$19,127	\$12,329	\$5,218	\$3,364	\$0	\$0
10	65,000	860,000	\$23,750	\$14,580	\$750	\$460	\$17,760	\$10,903	\$4,846	\$2,975	\$0	\$0
11	60,000	920,000	\$23,750	\$13,886	\$750	\$439	\$16,394	\$9,585	\$4,473	\$2,615	\$0	\$0
12	55,000	975,000	\$23,750	\$13,225	\$750	\$418	\$15,028	\$8,368	\$4,100	\$2,283	\$0	\$0
13	50,000	1,025,000	\$23,750	\$12,595	\$750	\$398	\$13,662	\$7,245	\$3,727	\$1,977	\$0	\$0
14	45,000	1,070,000	\$23,750	\$11,995	\$750	\$379	\$12,296	\$6,210	\$3,355	\$1,694	\$0	\$0
15	40,000	1,110,000	\$23,750	\$11,424	\$750	\$361	\$10,930	\$5,257	\$2,982	\$1,434	\$0	\$0
16	35,000	1,145,000	\$23,750	\$10,880	\$750	\$344	\$9,563	\$4,381	\$2,609	\$1,195	\$0	\$0
17	30,000	1,175,000	\$23,750	\$10,362	\$750	\$327	\$8,197	\$3,576	\$2,236	\$976	\$0	\$0
18	25,000	1,200,000	\$23,750	\$9,869	\$750	\$312	\$6,831	\$2,838	\$1,864	\$774	\$0	\$0
				\$244,763		\$7,729		\$232,464		\$63,425		\$0

Year	-----Periodic Costs-----		Conv'n Cost	Sum of Periodic	PV	Sum of	PV	Annual	PV	Cumulative	Operating	PV
	Engine Rebuild	Trap Replace			Sum of Periodic	Periodic Incr	SoP Incr	Operat'g Cost	Operating Cost	Operating Cost	Cost Incr	Opr Cost Incr
1	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$33,261	\$31,677	\$31,677	\$7,642	\$7,279
2	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$39,199	\$35,554	\$67,232	\$7,830	\$7,102
3	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$45,136	\$38,990	\$106,222	\$8,017	\$6,926
4	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$49,708	\$40,895	\$147,117	\$7,832	\$6,444
5	\$10,000	\$3,000	\$0	\$13,000	\$10,186	\$3,000	\$2,351	\$61,341	\$48,063	\$195,179	\$10,459	\$8,195
6	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$46,975	\$35,054	\$230,233	\$7,087	\$5,288
7	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$45,609	\$32,413	\$262,647	\$6,714	\$4,771
8	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$44,243	\$29,945	\$292,592	\$6,341	\$4,292
9	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$42,877	\$27,639	\$320,231	\$5,968	\$3,847
10	\$10,000	\$3,000	\$0	\$13,000	\$7,981	\$3,000	\$1,842	\$54,510	\$33,465	\$353,695	\$8,596	\$5,277
11	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$40,144	\$23,472	\$377,167	\$5,223	\$3,054
12	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$38,778	\$21,593	\$398,760	\$4,850	\$2,701
13	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$37,412	\$19,840	\$418,600	\$4,477	\$2,374
14	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$36,046	\$18,206	\$436,806	\$4,105	\$2,073
15	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$34,680	\$16,681	\$453,487	\$3,732	\$1,795
16	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$33,313	\$15,261	\$468,748	\$3,359	\$1,539
17	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$31,947	\$13,938	\$482,687	\$2,986	\$1,303
18	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$30,581	\$12,707	\$495,394	\$2,614	\$1,086
					\$18,167		\$4,192	Capital Cost=		\$202,000	Net Incr=	\$75,346
								Residual Value=		\$500		
								Life-cycle Cost=		\$696,894		
January 14, 1991												

January 14, 1991

Facility Capital Cost=
Facility Residual Value=

CASE IV - Propane

Year	Annual km	Cumulative km	Annual Bus Maint	PV Annual Bus Maint	Bus Maint Increm	PV Bus Maint Increm	Annual Fuel Bill	PV Annual Fuel Bill	Fuel Bill Increm	PV Fuel Bill Increm	Annual Overhead Increm	PV Annual Overhead Increm
1	100,000	100,000	\$6,125	\$5,833	\$375	\$357	\$19,589	\$18,657	(\$279)	(\$266)	\$100	\$95
2	100,000	200,000	\$12,250	\$11,111	\$750	\$680	\$19,589	\$17,768	(\$279)	(\$254)	\$100	\$91
3	100,000	300,000	\$18,375	\$15,873	\$1,125	\$972	\$19,589	\$16,922	(\$279)	(\$241)	\$100	\$86
4	95,000	395,000	\$24,500	\$20,156	\$1,500	\$1,234	\$18,610	\$15,310	(\$266)	(\$218)	\$100	\$82
5	90,000	485,000	\$24,500	\$19,196	\$1,500	\$1,175	\$17,630	\$13,814	(\$252)	(\$197)	\$100	\$78
6	85,000	570,000	\$24,500	\$18,282	\$1,500	\$1,119	\$16,651	\$12,425	(\$238)	(\$177)	\$100	\$75
7	80,000	650,000	\$24,500	\$17,412	\$1,500	\$1,066	\$15,671	\$11,137	(\$224)	(\$159)	\$100	\$71
8	75,000	725,000	\$24,500	\$16,583	\$1,500	\$1,015	\$14,692	\$9,944	(\$210)	(\$142)	\$100	\$68
9	70,000	795,000	\$24,500	\$15,793	\$1,500	\$967	\$13,713	\$8,839	(\$196)	(\$126)	\$100	\$64
10	65,000	860,000	\$24,500	\$15,041	\$1,500	\$921	\$12,733	\$7,817	(\$182)	(\$112)	\$100	\$61
11	60,000	920,000	\$24,500	\$14,325	\$1,500	\$877	\$11,754	\$6,872	(\$168)	(\$98)	\$100	\$58
12	55,000	975,000	\$24,500	\$13,643	\$1,500	\$835	\$10,774	\$5,999	(\$154)	(\$86)	\$100	\$56
13	50,000	1,025,000	\$24,500	\$12,993	\$1,500	\$795	\$9,795	\$5,194	(\$140)	(\$74)	\$100	\$53
14	45,000	1,070,000	\$24,500	\$12,374	\$1,500	\$758	\$8,815	\$4,452	(\$126)	(\$64)	\$100	\$51
15	40,000	1,110,000	\$24,500	\$11,785	\$1,500	\$722	\$7,836	\$3,769	(\$112)	(\$54)	\$100	\$48
16	35,000	1,145,000	\$24,500	\$11,224	\$1,500	\$687	\$6,856	\$3,141	(\$98)	(\$45)	\$100	\$46
17	30,000	1,175,000	\$24,500	\$10,689	\$1,500	\$654	\$5,877	\$2,564	(\$84)	(\$37)	\$100	\$44
18	25,000	1,200,000	\$24,500	\$10,180	\$1,500	\$623	\$4,897	\$2,035	(\$70)	(\$29)	\$100	\$42
				\$252,493		\$15,459		\$166,661		(\$2,378)		\$1,169

-----Periodic Costs-----

Year	Engine Rebuild	Converter Replace	Conv'n Cost	Sum of Periodic	PV Sum Periodic	Sum of Periodic Increm	PV SoP Increm	Annual Operat'g Cost	PV Operat'g Cost	Cumulative Operating Cost	Operating Cost Increm	PV Opr Cost Increm
1	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$25,814	\$24,585	\$24,585	\$196	\$186
2	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$31,939	\$28,970	\$53,555	\$571	\$517
3	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$38,064	\$32,881	\$86,436	\$946	\$817
4	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$43,210	\$35,549	\$121,985	\$1,334	\$1,098
5	\$10,000	\$1,000	\$0	\$11,000	\$8,619	\$1,000	\$784	\$53,230	\$41,707	\$163,693	\$2,348	\$1,840
6	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$41,251	\$30,782	\$194,475	\$1,362	\$1,017
7	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$40,271	\$28,620	\$223,095	\$1,376	\$978
8	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$39,292	\$26,594	\$249,689	\$1,390	\$941
9	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$38,313	\$24,697	\$274,386	\$1,404	\$905
10	\$10,000	\$1,000	\$0	\$11,000	\$6,753	\$1,000	\$614	\$48,333	\$29,672	\$304,058	\$2,418	\$1,485
11	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$36,354	\$21,255	\$325,314	\$1,432	\$837
12	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$35,374	\$19,698	\$345,011	\$1,446	\$805
13	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$34,395	\$18,240	\$363,251	\$1,460	\$774
14	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$33,415	\$16,877	\$380,128	\$1,474	\$745
15	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$32,436	\$15,602	\$395,730	\$1,488	\$716
16	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$31,456	\$14,410	\$410,141	\$1,502	\$688
17	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$30,477	\$13,297	\$423,438	\$1,516	\$661
18	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,497	\$12,257	\$435,695	\$1,530	\$636
					\$15,372		\$1,397					

Facility Capital Cost=
Facility Residual Value=

\$6,000
\$0

Capital Cost=
Residual Value=
Life-cycle Cost=

\$200,000
\$500
\$641,195

Net Incr=

\$15,647

January 14, 1991

CASE V - Natural Gas

CASE V - Natural Gas			PV		PV		PV		PV		PV	
	Annual	Cumulative	Annual	Bus	Bus	Annual	Annual	Fuel	Fuel	Annual	Annual	
Year	km	km	Bus	Bus	Maint	Maint	Fuel	Fuel	Bill	Bill	Overhead	Overhead
			Maint	Maint	Increm	Increm	Bill	Bill	Increm	Increm	Increm	Increm
1	100,000	100,000	\$6,125	\$5,833	\$375	\$357	\$9,085	\$8,653	(\$10,784)	(\$10,270)	\$577	\$550
2	100,000	200,000	\$12,250	\$11,111	\$750	\$680	\$9,085	\$8,241	(\$10,784)	(\$9,781)	\$577	\$523
3	100,000	300,000	\$18,375	\$15,873	\$1,125	\$972	\$9,085	\$7,848	(\$10,784)	(\$9,315)	\$1,577	\$1,362
4	95,000	395,000	\$24,500	\$20,156	\$1,500	\$1,234	\$8,631	\$7,101	(\$10,244)	(\$8,428)	\$577	\$475
5	90,000	485,000	\$24,500	\$19,196	\$1,500	\$1,175	\$8,177	\$6,407	(\$9,705)	(\$7,604)	\$577	\$452
6	85,000	570,000	\$24,500	\$18,282	\$1,500	\$1,119	\$7,723	\$5,763	(\$9,166)	(\$6,840)	\$1,577	\$1,177
7	80,000	650,000	\$24,500	\$17,412	\$1,500	\$1,066	\$7,268	\$5,165	(\$8,627)	(\$6,131)	\$577	\$410
8	75,000	725,000	\$24,500	\$16,583	\$1,500	\$1,015	\$6,814	\$4,612	(\$8,088)	(\$5,474)	\$577	\$391
9	70,000	795,000	\$24,500	\$15,793	\$1,500	\$967	\$6,360	\$4,100	(\$7,548)	(\$4,866)	\$1,577	\$1,017
10	65,000	860,000	\$24,500	\$15,041	\$1,500	\$921	\$5,905	\$3,625	(\$7,009)	(\$4,303)	\$577	\$354
11	60,000	920,000	\$24,500	\$14,325	\$1,500	\$877	\$5,451	\$3,187	(\$6,470)	(\$3,783)	\$577	\$337
12	55,000	975,000	\$24,500	\$13,643	\$1,500	\$835	\$4,997	\$2,782	(\$5,931)	(\$3,303)	\$1,577	\$878
13	50,000	1,025,000	\$24,500	\$12,993	\$1,500	\$795	\$4,543	\$2,409	(\$5,392)	(\$2,859)	\$577	\$306
14	45,000	1,070,000	\$24,500	\$12,374	\$1,500	\$758	\$4,088	\$2,065	(\$4,853)	(\$2,451)	\$577	\$291
15	40,000	1,110,000	\$24,500	\$11,785	\$1,500	\$722	\$3,634	\$1,748	(\$4,313)	(\$2,075)	\$1,577	\$759
16	35,000	1,145,000	\$24,500	\$11,224	\$1,500	\$687	\$3,180	\$1,457	(\$3,774)	(\$1,729)	\$577	\$264
17	30,000	1,175,000	\$24,500	\$10,689	\$1,500	\$654	\$2,726	\$1,189	(\$3,235)	(\$1,411)	\$577	\$252
18	25,000	1,200,000	\$24,500	\$10,180	\$1,500	\$623	\$2,271	\$944	(\$2,696)	(\$1,120)	\$1,577	\$655
				\$252,493		\$15,459		\$77,296		(\$91,743)		\$10,453

----Periodic Costs----					PV	Sum of	PV	Annual	PV	Cumulative	Operating	PV
Year	Engine Rebuild	Converter Replace	Conv'n Cost	Sum of Periodic	Sum of Periodic	Periodic Increm	SoP Increm	Operat'g Cost	Operat'g Cost	Operating Cost	Cost Increm	Opr Cost Increm
1	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$15,787	\$15,036	\$15,036	(\$9,832)	(\$9,363)
2	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$21,912	\$19,875	\$34,911	(\$9,457)	(\$8,577)
3	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,037	\$25,084	\$59,994	(\$8,082)	(\$6,981)
4	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$33,708	\$27,732	\$87,726	(\$8,167)	(\$6,719)
5	\$10,000	\$1,000	\$0	\$11,000	\$6,619	\$1,000	\$784	\$44,254	\$34,674	\$122,400	(\$6,628)	(\$5,193)
6	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$33,800	\$25,222	\$147,622	(\$6,089)	(\$4,544)
7	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$32,345	\$22,987	\$170,609	(\$6,550)	(\$4,655)
8	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$31,891	\$21,585	\$192,194	(\$6,011)	(\$4,068)
9	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$32,437	\$20,909	\$213,103	(\$4,471)	(\$2,882)
10	\$10,000	\$1,000	\$0	\$11,000	\$6,753	\$1,000	\$614	\$41,982	\$25,774	\$238,877	(\$3,932)	(\$2,414)
11	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$30,528	\$17,849	\$256,726	(\$4,393)	(\$2,569)
12	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$31,074	\$17,303	\$274,029	(\$2,854)	(\$1,589)
13	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,620	\$15,708	\$289,737	(\$3,315)	(\$1,758)
14	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,165	\$14,731	\$304,467	(\$2,776)	(\$1,402)
15	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,711	\$14,292	\$318,759	(\$1,236)	(\$595)
16	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$28,257	\$12,945	\$331,704	(\$1,697)	(\$778)
17	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$27,803	\$12,130	\$343,834	(\$1,158)	(\$505)
18	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$28,348	\$11,779	\$355,613	\$381	\$158
					\$15,372		\$1,397	Capital Cost=		\$220,000	Net Incr=	(\$64,434)
Facility Capital Cost=						\$28,000		Residual Value=		\$500		
Facility Residual Value=						\$0		Life-cycle Cost=		\$603,113		

January 14, 1991

CASE VI - Methanol

Year	Annual km	Cumulative km	PV		Bus Maint Incr	PV		Annual Fuel Bill	PV		Fuel Bill Incr	PV		Annual Overhead Incr	PV	
			Annual Bus Maint	Annual Bus Maint		Bus Maint Incr	Bus Maint Incr		Annual Fuel Bill	Annual Fuel Bill		Fuel Bill Incr	Fuel Bill Incr		Annual Overhead Incr	Annual Overhead Incr
1	100,000	100,000	\$6,125	\$5,833	\$375		\$357	\$23,313	\$22,203	\$3,444	\$3,280	\$100		\$95		
2	100,000	200,000	\$12,250	\$11,111	\$750		\$680	\$23,313	\$21,146	\$3,444	\$3,124	\$100		\$91		
3	100,000	300,000	\$18,375	\$15,873	\$1,125		\$972	\$23,313	\$20,139	\$3,444	\$2,975	\$100		\$86		
4	95,000	395,000	\$24,500	\$20,156	\$1,500		\$1,234	\$22,147	\$18,221	\$3,272	\$2,692	\$100		\$82		
5	90,000	485,000	\$24,500	\$19,196	\$1,500		\$1,175	\$20,982	\$16,440	\$3,100	\$2,429	\$100		\$78		
6	85,000	570,000	\$24,500	\$18,282	\$1,500		\$1,119	\$19,816	\$14,787	\$2,928	\$2,185	\$100		\$75		
7	80,000	650,000	\$24,500	\$17,412	\$1,500		\$1,066	\$18,650	\$13,255	\$2,755	\$1,958	\$100		\$71		
8	75,000	725,000	\$24,500	\$16,583	\$1,500		\$1,015	\$17,485	\$11,834	\$2,583	\$1,748	\$100		\$68		
9	70,000	795,000	\$24,500	\$15,793	\$1,500		\$967	\$16,319	\$10,519	\$2,411	\$1,554	\$100		\$64		
10	65,000	860,000	\$24,500	\$15,041	\$1,500		\$921	\$15,153	\$9,303	\$2,239	\$1,374	\$100		\$61		
11	60,000	920,000	\$24,500	\$14,325	\$1,500		\$877	\$13,988	\$8,178	\$2,067	\$1,208	\$100		\$58		
12	55,000	975,000	\$24,500	\$13,643	\$1,500		\$835	\$12,822	\$7,140	\$1,894	\$1,055	\$100		\$56		
13	50,000	1,025,000	\$24,500	\$12,993	\$1,500		\$795	\$11,657	\$6,182	\$1,722	\$913	\$100		\$53		
14	45,000	1,070,000	\$24,500	\$12,374	\$1,500		\$758	\$10,491	\$5,299	\$1,550	\$783	\$100		\$51		
15	40,000	1,110,000	\$24,500	\$11,785	\$1,500		\$722	\$9,325	\$4,486	\$1,378	\$663	\$100		\$48		
16	35,000	1,145,000	\$24,500	\$11,224	\$1,500		\$687	\$8,160	\$3,738	\$1,205	\$552	\$100		\$46		
17	30,000	1,175,000	\$24,500	\$10,689	\$1,500		\$654	\$6,994	\$3,051	\$1,033	\$451	\$100		\$44		
18	25,000	1,200,000	\$24,500	\$10,180	\$1,500		\$623	\$5,828	\$2,422	\$861	\$358	\$100		\$42		
			\$252,493				\$15,459			\$198,341			\$29,302			\$1,169

-----Periodic Costs-----												
Year	Engine Rebuild	Catalyst Replace	Conv'n Cost	Sum of Periodic	PV Sum of Periodic	Sum of Periodic Incr	PV SoP Incr	Annual Operat'g Cost	PV Operat'g Cost	Cumulative Operating Cost	Operating Cost Incr	PV Opr Cost Incr
1	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$29,538	\$28,131	\$28,131	\$3,919	\$3,733
2	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$35,663	\$32,347	\$60,479	\$4,294	\$3,895
3	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$41,788	\$36,098	\$96,577	\$4,669	\$4,033
4	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$46,747	\$38,459	\$135,036	\$4,872	\$4,008
5	\$10,000	\$1,000	\$0	\$11,000	\$8,619	\$1,000	\$784	\$56,582	\$44,333	\$179,369	\$5,700	\$4,466
6	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$44,416	\$33,144	\$212,513	\$4,528	\$3,379
7	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$43,250	\$30,737	\$243,251	\$4,355	\$3,095
8	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$42,085	\$28,485	\$271,735	\$4,183	\$2,831
9	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$40,919	\$26,377	\$298,112	\$4,011	\$2,585
10	\$10,000	\$1,000	\$0	\$11,000	\$6,753	\$1,000	\$614	\$50,753	\$31,158	\$329,270	\$4,839	\$2,971
11	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$38,588	\$22,561	\$351,832	\$3,667	\$2,144
12	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$37,422	\$20,838	\$372,670	\$3,484	\$1,946
13	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$36,257	\$19,228	\$391,897	\$3,322	\$1,762
14	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$35,091	\$17,723	\$409,621	\$3,150	\$1,591
15	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$33,925	\$16,319	\$425,939	\$2,978	\$1,432
16	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$32,760	\$15,008	\$440,947	\$2,805	\$1,285
17	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$31,594	\$13,784	\$454,731	\$2,633	\$1,149
18	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$30,428	\$12,644	\$467,375	\$2,461	\$1,023
					\$15,372		\$1,397	Capital Cost=		\$200,000	Net Incr=	\$47,327
Facility Capital Cost=						\$8,000		Residual Value=		\$500		
Facility Residual Value=						\$0		Life-cycle Cost=		\$674,875		
January 14, 1991												

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CASE VII - Trolley, No Overhead

Year			PV		PV		PV		PV		PV	
	Annual km	Cumulative km	Annual Bus Maint	Annual Bus Maint	Bus Maint Incr	Bus Maint Incr	Annual Fuel Bill	Annual Fuel Bill	Fuel Bill Incr	Fuel Bill Incr	Annual Overhead Incr	Annual Overhead Incr
1	100,000	100,000	\$5,750	\$5,476	\$0	\$0	\$19,272	\$18,354	(\$597)	(\$568)	\$5,977	\$5,692
2	100,000	200,000	\$11,500	\$10,431	\$0	\$0	\$19,272	\$17,480	(\$597)	(\$541)	\$5,977	\$5,421
3	100,000	300,000	\$17,250	\$14,901	\$0	\$0	\$19,272	\$16,648	(\$597)	(\$516)	\$5,977	\$5,163
4	95,000	395,000	\$23,000	\$18,922	\$0	\$0	\$18,308	\$15,062	(\$567)	(\$466)	\$5,977	\$4,917
5	90,000	485,000	\$23,000	\$18,021	\$0	\$0	\$17,345	\$13,590	(\$537)	(\$421)	\$5,977	\$4,683
6	85,000	570,000	\$23,000	\$17,163	\$0	\$0	\$16,381	\$12,224	(\$507)	(\$379)	\$5,977	\$4,460
7	80,000	650,000	\$23,000	\$16,346	\$0	\$0	\$15,418	\$10,957	(\$477)	(\$339)	\$5,977	\$4,248
8	75,000	725,000	\$23,000	\$15,567	\$0	\$0	\$14,454	\$9,783	(\$448)	(\$303)	\$5,977	\$4,045
9	70,000	795,000	\$23,000	\$14,826	\$0	\$0	\$13,490	\$8,696	(\$418)	(\$269)	\$5,977	\$3,853
10	65,000	860,000	\$23,000	\$14,120	\$0	\$0	\$12,527	\$7,690	(\$388)	(\$238)	\$5,977	\$3,669
11	60,000	920,000	\$23,000	\$13,448	\$0	\$0	\$11,563	\$6,761	(\$358)	(\$209)	\$5,977	\$3,495
12	55,000	975,000	\$23,000	\$12,807	\$0	\$0	\$10,600	\$5,902	(\$328)	(\$183)	\$5,977	\$3,328
13	50,000	1,025,000	\$23,000	\$12,197	\$0	\$0	\$9,636	\$5,110	(\$298)	(\$158)	\$5,977	\$3,170
14	45,000	1,070,000	\$23,000	\$11,617	\$0	\$0	\$8,672	\$4,380	(\$269)	(\$136)	\$5,977	\$3,019
15	40,000	1,110,000	\$23,000	\$11,063	\$0	\$0	\$7,709	\$3,708	(\$239)	(\$115)	\$5,977	\$2,875
16	35,000	1,145,000	\$23,000	\$10,537	\$0	\$0	\$6,745	\$3,090	(\$209)	(\$96)	\$5,977	\$2,738
17	30,000	1,175,000	\$23,000	\$10,035	\$0	\$0	\$5,782	\$2,522	(\$179)	(\$78)	\$5,977	\$2,608
18	25,000	1,200,000	\$23,000	\$9,557	\$0	\$0	\$4,818	\$2,002	(\$149)	(\$62)	\$5,977	\$2,484
			\$237,034		\$0		\$163,961		(\$5,078)		\$69,869	

-----Periodic Costs-----

-----Periodic Costs-----				PV	Sum of	PV	Annual	PV	Cumulative	Operating	PV
	Motor		Conv'n	Sum of	Sum of	Periodic	Operat'g	Operating	Operating	Cost	Opr Cost
Year	Rebuild		Cost	Periodic	Periodic	Incr	Cost	Cost	Cost	Incr	Incr
1	\$0	\$0	\$0	\$0	\$0	\$0	\$30,999	\$29,523	\$29,523	\$5,380	\$5,124
2	\$1,600	\$0	\$0	\$1,600	\$1,451	\$1,600	\$38,349	\$34,784	\$64,307	\$6,980	\$6,331
3	\$1,600	\$0	\$0	\$1,600	\$1,382	\$1,600	\$44,099	\$38,094	\$102,401	\$6,980	\$6,030
4	\$1,600	\$0	\$0	\$1,600	\$1,316	\$1,600	\$48,885	\$40,218	\$142,619	\$7,010	\$5,767
5	\$0	\$0	\$0	\$0	\$0	(\$10,000)	\$46,322	\$36,294	\$178,913	(\$4,560)	(\$3,573)
6	\$1,600	\$0	\$0	\$1,600	\$1,194	\$1,600	\$46,958	\$35,041	\$213,954	\$7,070	\$5,276
7	\$1,600	\$0	\$0	\$1,600	\$1,137	\$1,600	\$45,995	\$32,688	\$246,642	\$7,100	\$5,046
8	\$0	\$0	\$0	\$0	\$0	\$0	\$43,431	\$29,396	\$276,038	\$5,529	\$3,742
9	\$1,600	\$0	\$0	\$1,600	\$1,031	\$1,600	\$44,067	\$28,406	\$304,444	\$7,159	\$4,615
10	\$0	\$0	\$0	\$0	\$0	(\$10,000)	\$41,504	\$25,480	\$329,924	(\$4,411)	(\$2,708)
11	\$1,600	\$0	\$0	\$1,600	\$935	\$1,600	\$42,140	\$24,639	\$354,562	\$7,219	\$4,221
12	\$0	\$0	\$0	\$0	\$0	\$0	\$39,577	\$22,038	\$376,600	\$5,649	\$3,145
13	\$1,600	\$0	\$0	\$1,600	\$849	\$1,600	\$40,213	\$21,326	\$397,926	\$7,279	\$3,860
14	\$0	\$0	\$0	\$0	\$0	\$0	\$37,649	\$19,016	\$416,941	\$5,708	\$2,883
15	\$0	\$0	\$0	\$0	\$0	\$0	\$36,686	\$17,646	\$434,588	\$5,738	\$2,780
16	\$0	\$0	\$0	\$0	\$0	\$0	\$35,722	\$16,365	\$450,952	\$5,768	\$2,642
17	\$1,600	\$0	\$0	\$1,600	\$698	\$1,600	\$36,359	\$15,863	\$466,816	\$7,398	\$3,228
18	\$0	\$0	\$0	\$0	\$0	\$0	\$33,795	\$14,043	\$480,858	\$5,828	\$2,422
					\$9,994	(\$3,980)	Capital Cost=		\$427,000	Net Incr=	\$60,811

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CASE VIII - Trolley With Overhead

Year	Annual km	Cumulative km	Annual Bus Maint	PV Annual Bus Maint	Bus Maint Increm	PV Bus Maint Increm	Annual Fuel Bill	PV Annual Fuel Bill	Fuel Bill Increm	PV Fuel Bill Increm	Annual Overhead Increm	PV Annual Overhead Increm
1	100,000	100,000	\$5,750	\$5,476	\$0	\$0	\$19,272	\$18,354	(\$597)	(\$568)	\$5,977	\$5,692
2	100,000	200,000	\$11,500	\$10,431	\$0	\$0	\$19,272	\$17,480	(\$597)	(\$541)	\$5,977	\$5,421
3	100,000	300,000	\$17,250	\$14,901	\$0	\$0	\$19,272	\$16,648	(\$597)	(\$516)	\$5,977	\$5,163
4	95,000	395,000	\$23,000	\$18,922	\$0	\$0	\$18,308	\$15,062	(\$567)	(\$466)	\$5,977	\$4,917
5	90,000	485,000	\$23,000	\$18,021	\$0	\$0	\$17,345	\$13,590	(\$537)	(\$421)	\$5,977	\$4,683
6	85,000	570,000	\$23,000	\$17,163	\$0	\$0	\$16,381	\$12,224	(\$507)	(\$379)	\$5,977	\$4,460
7	80,000	650,000	\$23,000	\$16,346	\$0	\$0	\$15,418	\$10,957	(\$477)	(\$339)	\$5,977	\$4,248
8	75,000	725,000	\$23,000	\$15,567	\$0	\$0	\$14,454	\$9,783	(\$448)	(\$303)	\$5,977	\$4,045
9	70,000	795,000	\$23,000	\$14,826	\$0	\$0	\$13,490	\$8,696	(\$418)	(\$269)	\$5,977	\$3,853
10	65,000	860,000	\$23,000	\$14,120	\$0	\$0	\$12,527	\$7,690	(\$388)	(\$238)	\$5,977	\$3,669
11	60,000	920,000	\$23,000	\$13,448	\$0	\$0	\$11,563	\$6,761	(\$358)	(\$209)	\$5,977	\$3,495
12	55,000	975,000	\$23,000	\$12,807	\$0	\$0	\$10,600	\$5,902	(\$328)	(\$183)	\$5,977	\$3,328
13	50,000	1,025,000	\$23,000	\$12,197	\$0	\$0	\$9,636	\$5,110	(\$298)	(\$158)	\$5,977	\$3,170
14	45,000	1,070,000	\$23,000	\$11,617	\$0	\$0	\$8,672	\$4,380	(\$269)	(\$136)	\$5,977	\$3,019
15	40,000	1,110,000	\$23,000	\$11,063	\$0	\$0	\$7,709	\$3,708	(\$239)	(\$115)	\$5,977	\$2,875
16	35,000	1,145,000	\$23,000	\$10,537	\$0	\$0	\$6,745	\$3,090	(\$209)	(\$96)	\$5,977	\$2,738
17	30,000	1,175,000	\$23,000	\$10,035	\$0	\$0	\$5,782	\$2,522	(\$179)	(\$78)	\$5,977	\$2,608
18	25,000	1,200,000	\$23,000	\$9,557	\$0	\$0	\$4,818	\$2,002	(\$149)	(\$62)	\$5,977	\$2,484
				\$237,034		\$0		\$163,961		(\$5,078)		\$69,869

-----Periodic Costs-----

Year	Motor Rebuild	Conv'n Cost	Sum of Periodic	PV Sum of Periodic	Sum of Periodic Increm	PV Sum of Periodic Increm	Annual Operat'g Cost	PV Operating Cost	Cumulative Operating Cost	Operating Cost Increm	PV Opr Cost Increm
1	\$0	\$0	\$0	\$0	\$0	\$0	\$30,999	\$29,523	\$29,523	\$5,380	\$5,124
2	\$1,600	\$0	\$1,600	\$1,451	\$1,600	\$1,451	\$38,349	\$34,784	\$64,307	\$6,980	\$6,331
3	\$1,600	\$0	\$1,600	\$1,382	\$1,600	\$1,382	\$44,099	\$38,094	\$102,401	\$6,980	\$6,030
4	\$1,600	\$0	\$1,600	\$1,316	\$1,600	\$1,316	\$48,885	\$40,218	\$142,619	\$7,010	\$5,767
5	\$0	\$0	\$0	\$0	(\$10,000)	(\$7,835)	\$46,322	\$36,294	\$178,913	(\$4,560)	(\$3,573)
6	\$1,600	\$0	\$1,600	\$1,194	\$1,600	\$1,194	\$46,958	\$35,041	\$213,954	\$7,070	\$5,276
7	\$1,600	\$0	\$1,600	\$1,137	\$1,600	\$1,137	\$45,995	\$32,688	\$246,642	\$7,100	\$5,046
8	\$0	\$0	\$0	\$0	\$0	\$0	\$43,431	\$29,396	\$276,038	\$5,529	\$3,742
9	\$1,600	\$0	\$1,600	\$1,031	\$1,600	\$1,031	\$44,067	\$28,406	\$304,444	\$7,159	\$4,615
10	\$0	\$0	\$0	\$0	(\$10,000)	(\$6,139)	\$41,504	\$25,480	\$329,924	(\$4,411)	(\$2,708)
11	\$1,600	\$0	\$1,600	\$935	\$1,600	\$935	\$42,140	\$24,639	\$354,562	\$7,219	\$4,221
12	\$0	\$0	\$0	\$0	\$0	\$0	\$39,577	\$22,038	\$376,600	\$5,649	\$3,145
13	\$1,600	\$0	\$1,600	\$849	\$1,600	\$849	\$40,213	\$21,326	\$397,926	\$7,279	\$3,860
14	\$0	\$0	\$0	\$0	\$0	\$0	\$37,649	\$19,016	\$416,941	\$5,708	\$2,883
15	\$0	\$0	\$0	\$0	\$0	\$0	\$36,886	\$17,646	\$434,588	\$5,738	\$2,760
16	\$0	\$0	\$0	\$0	\$0	\$0	\$35,722	\$16,365	\$450,952	\$5,768	\$2,642
17	\$1,600	\$0	\$1,600	\$698	\$1,600	\$698	\$36,359	\$15,863	\$466,816	\$7,398	\$3,228
18	\$0	\$0	\$0	\$0	\$0	\$0	\$33,795	\$14,043	\$480,858	\$5,828	\$2,422
				\$9,994		(\$3,980)	Capital Cost=		\$427,000	Net Incr=	\$60,811
				Facility Capital Cost=	\$925,650		Residual Value=		\$125,000		
				Facility Residual Value=	\$462,825		Life-cycle Cost=		\$1,245,683		

January 14, 1991